The Quest for the Origin of the Proton's Sea
SeaQuest and SeaTEQ

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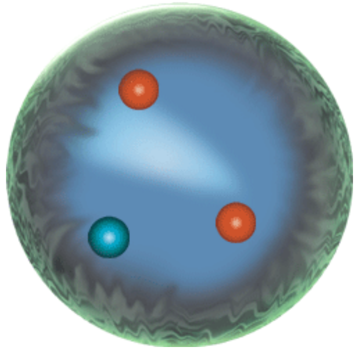
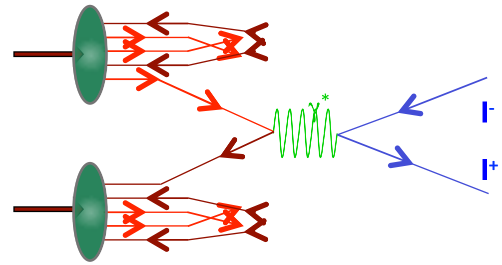
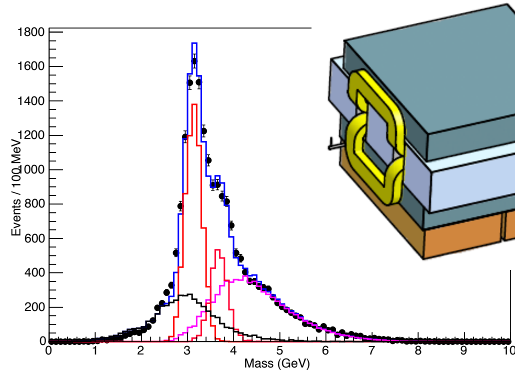
Physics Division

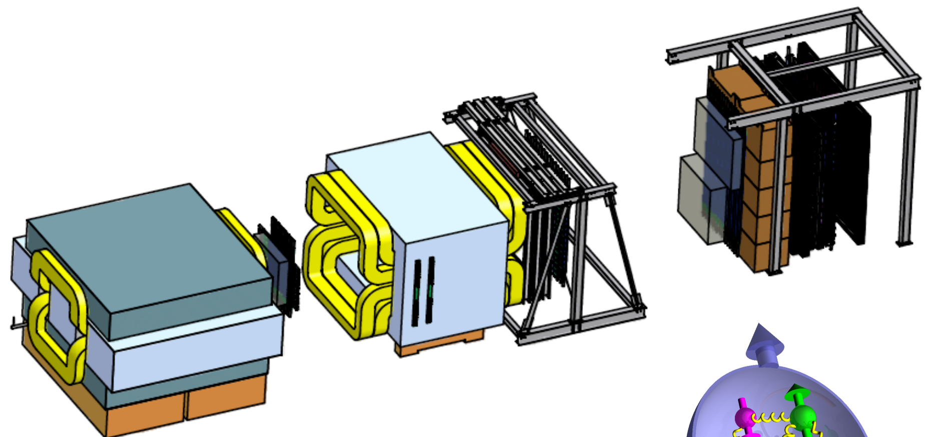
Argonne National Laboratory

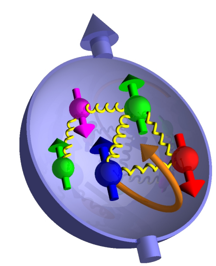
5 November 2015







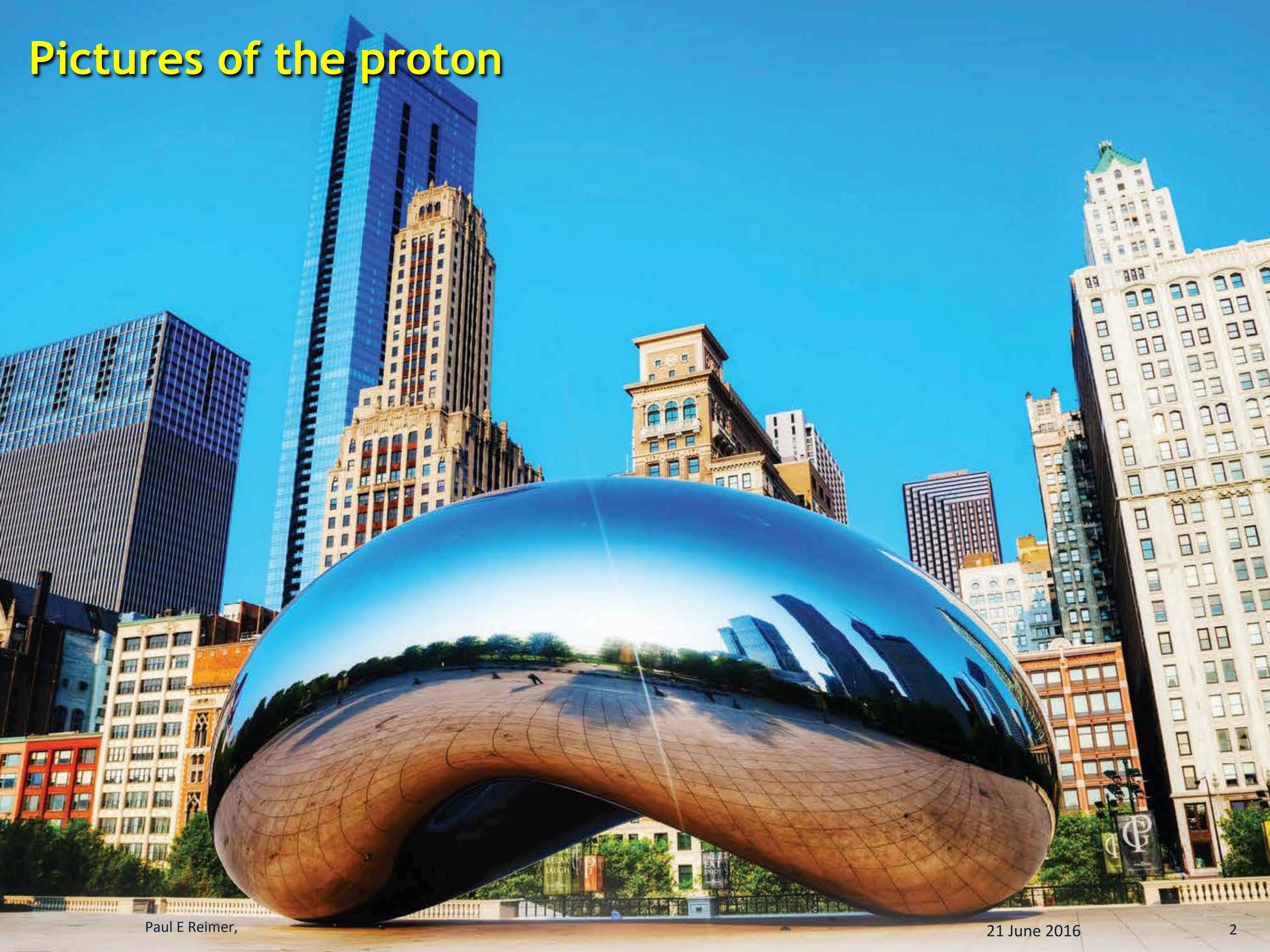




$$f_{1T}^{\perp}\big|_{\mathrm{SIDIS}} = -\, f_{1T}^{\perp}\big|_{\mathrm{DY}}$$

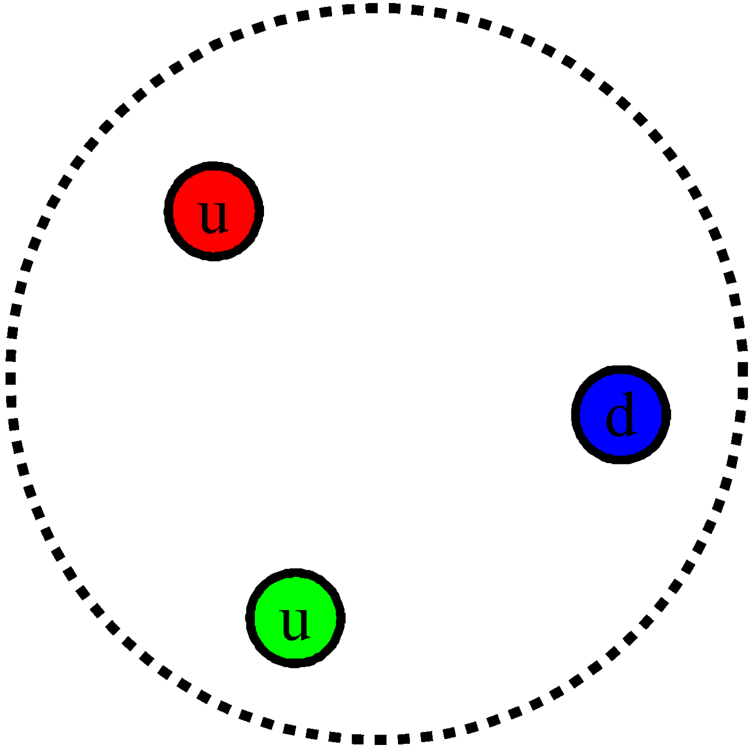
This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

Pictures of the proton

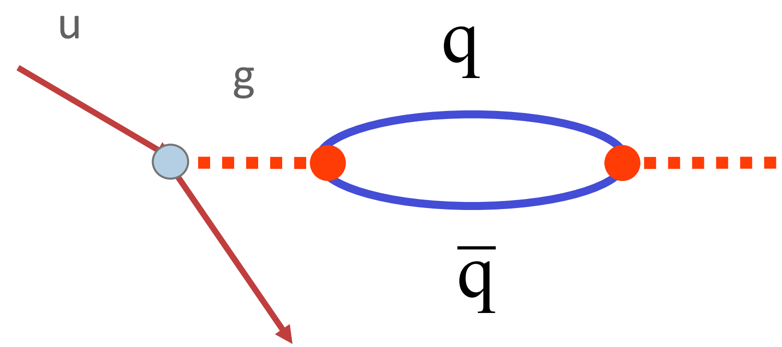


First picture of the proton: Valence quarks

- Constituent Quark/Bag Model motivated valence approach
  - Use valence-like (primordial) quark distributions at some very low scale, Q^2, perhaps a few hundred MeV
  - Radiatively generate sea and glue.   Gluck, Godbole, Reya, ZPC **41** 667 (1989)



Second Picture: Dynamics



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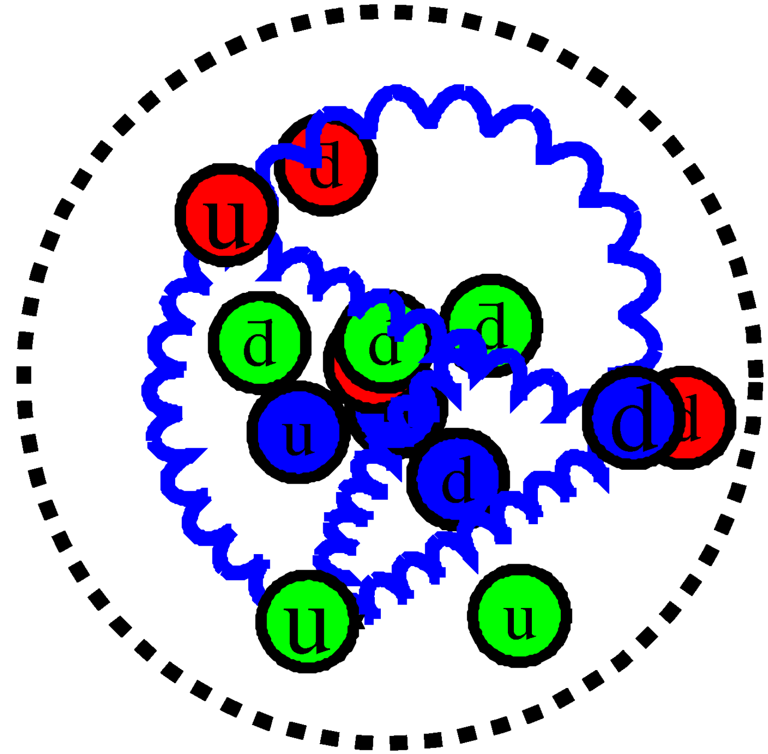


Sea is a fundamental part of the proton

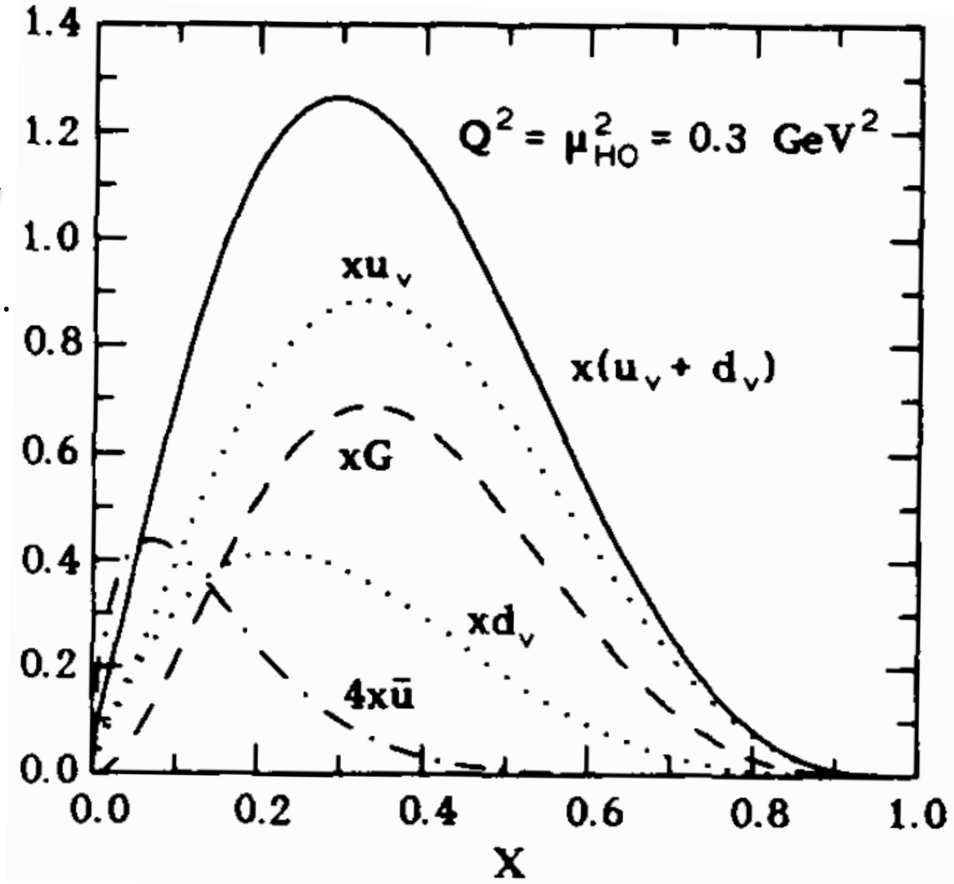
Parton distributions for high energy collisions

M. Glück, E. Reya, A. Vogt
Institut für Physik, Universität Dortmund, Postfach 500500, W-4600 Dortmund 50, Federal Republic of Germany

Received 10 June 1991

Abstract. Recent data from deep inelastic scattering experiments at $x > 10^{-2}$ are used to fix the parton distributions down to $x = 10^{-4}$ and $Q^2 = 0.3\ GeV^2$. **The predicted extrapolations are uniquely determined by the requirement of a *valence*-like structure of *all* parton distributions at some low resolution scale** . . . .

Gluck, Reya, Vogt, ZPC 53, 127 (1992)



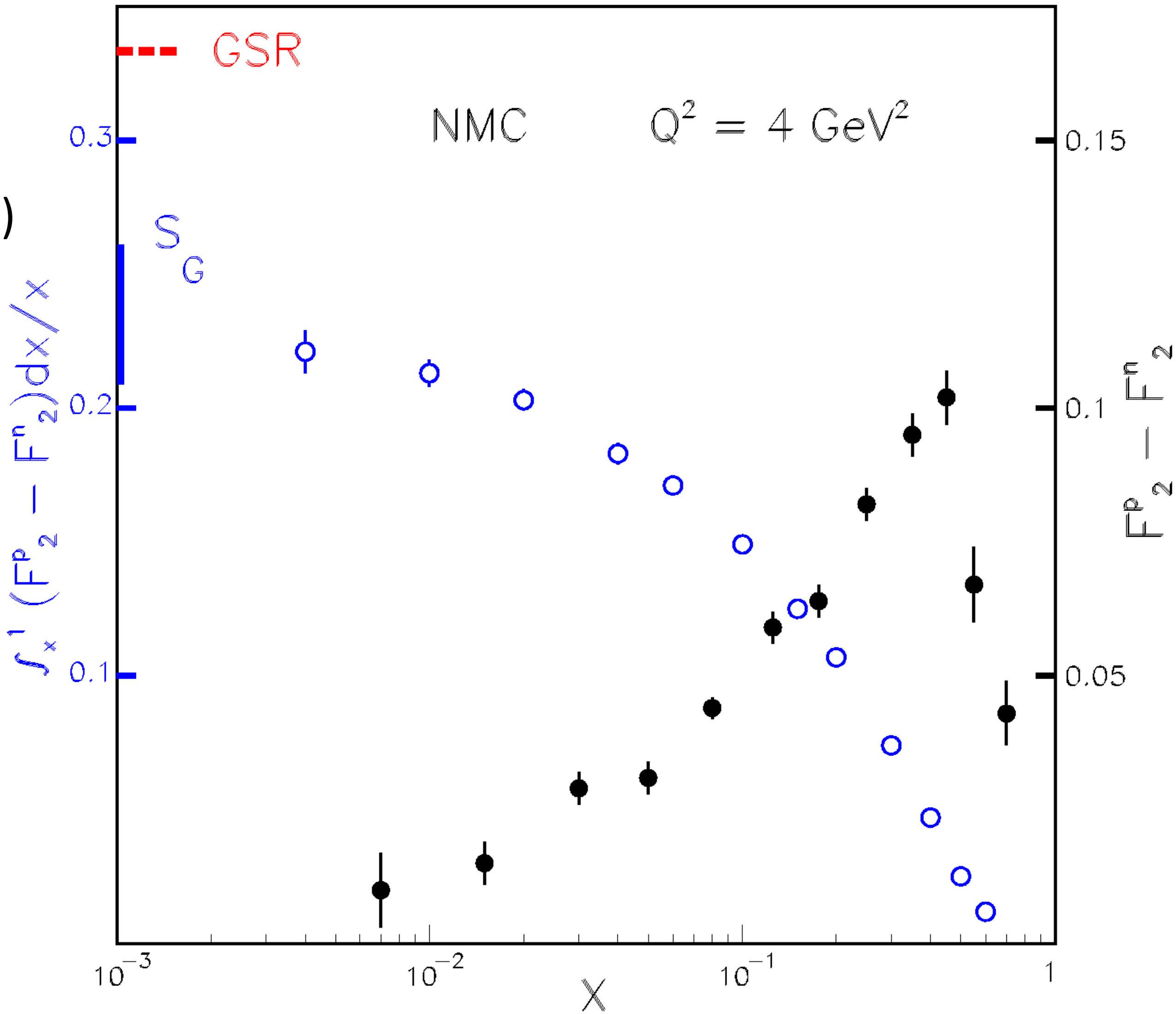
Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

$$\bar{d}(x) = \bar{u}(x)$$

- NMC (Gottfried Sum Rule)

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$



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$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$

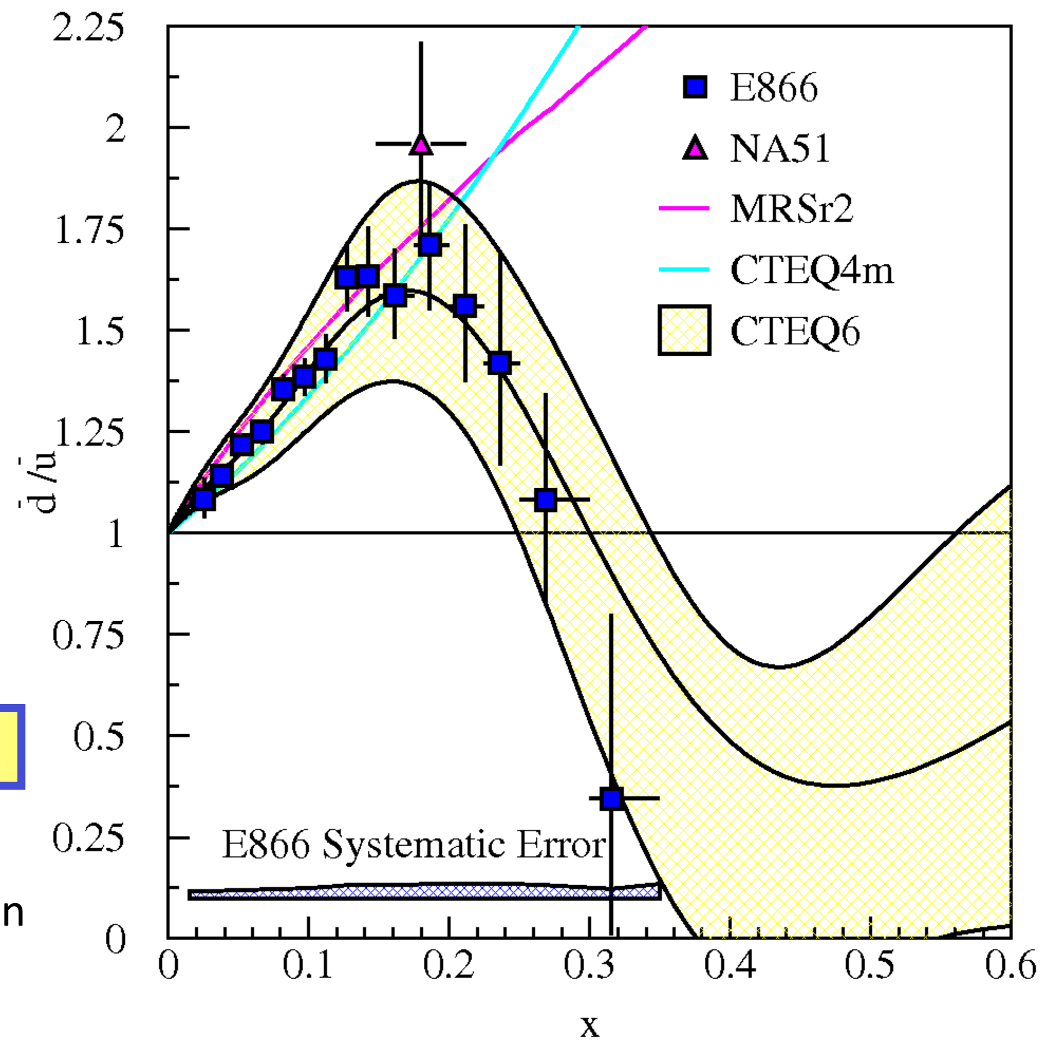
- NA51 (Drell-Yan)

$$\bar{d} > \bar{u} \text{ at } x = 0.18$$

- E866/NuSea (Drell-Yan)

$$\bar{d}(x)/\bar{u}(x) \text{ for } 0.015 \leq x \leq 0.35$$

- Knowledge of sea dist. are data driven



- Non perturbative QCD models can explain excess d-bar quarks, but not return to symmetry or deficit of d-bar quarks

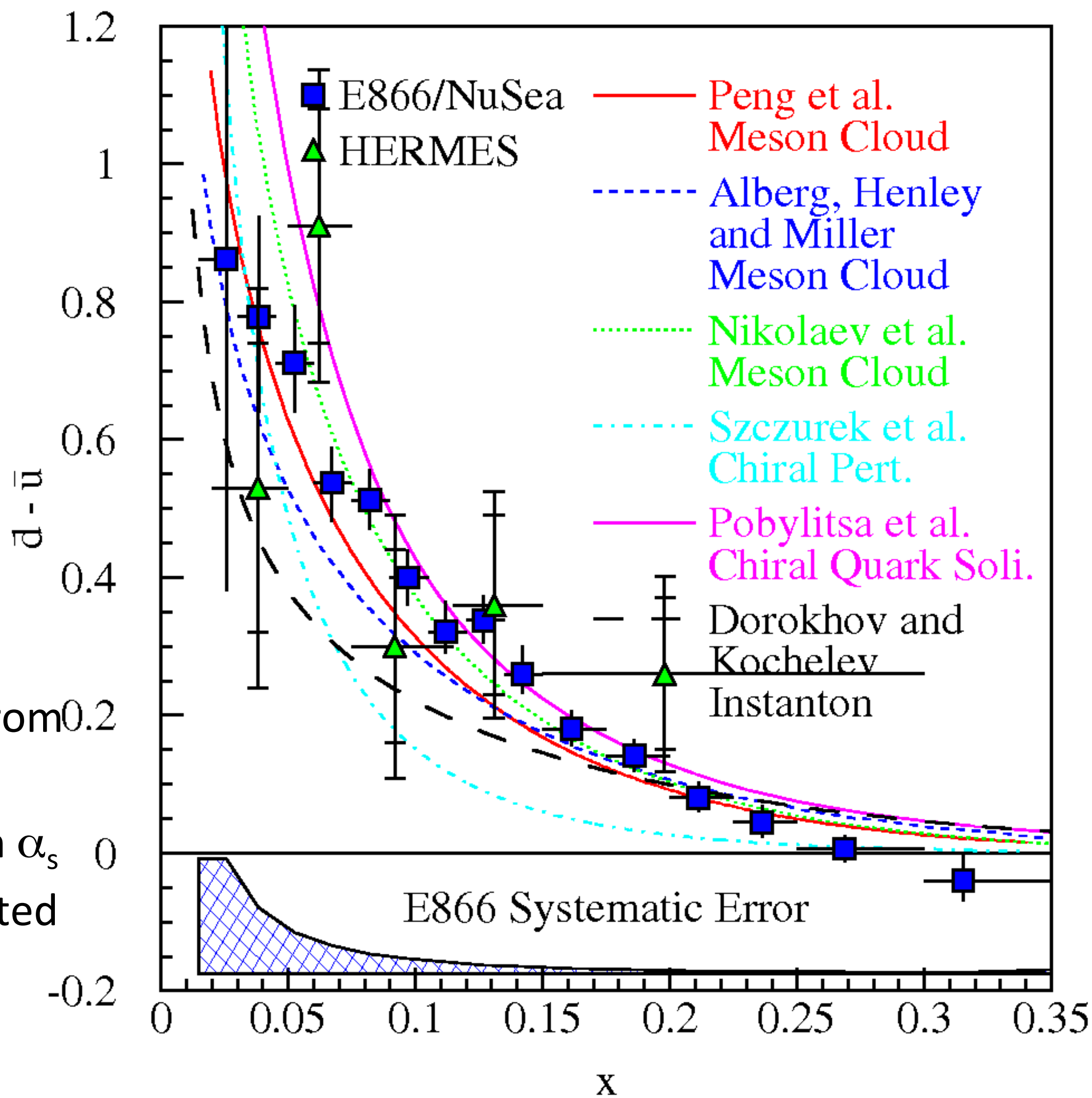
Proton Structure: By What Process Is the Sea Created?

- There is a gluon splitting component which is symmetric

$$\bar{d}(x) = \bar{d}_{\mathrm{pQCD}}(x) + \bar{d}_{\pi}(x)$$
$$\bar{u}(x) = \bar{u}_{\mathrm{pQCD}}(x) + \bar{u}_{\pi}(x)$$

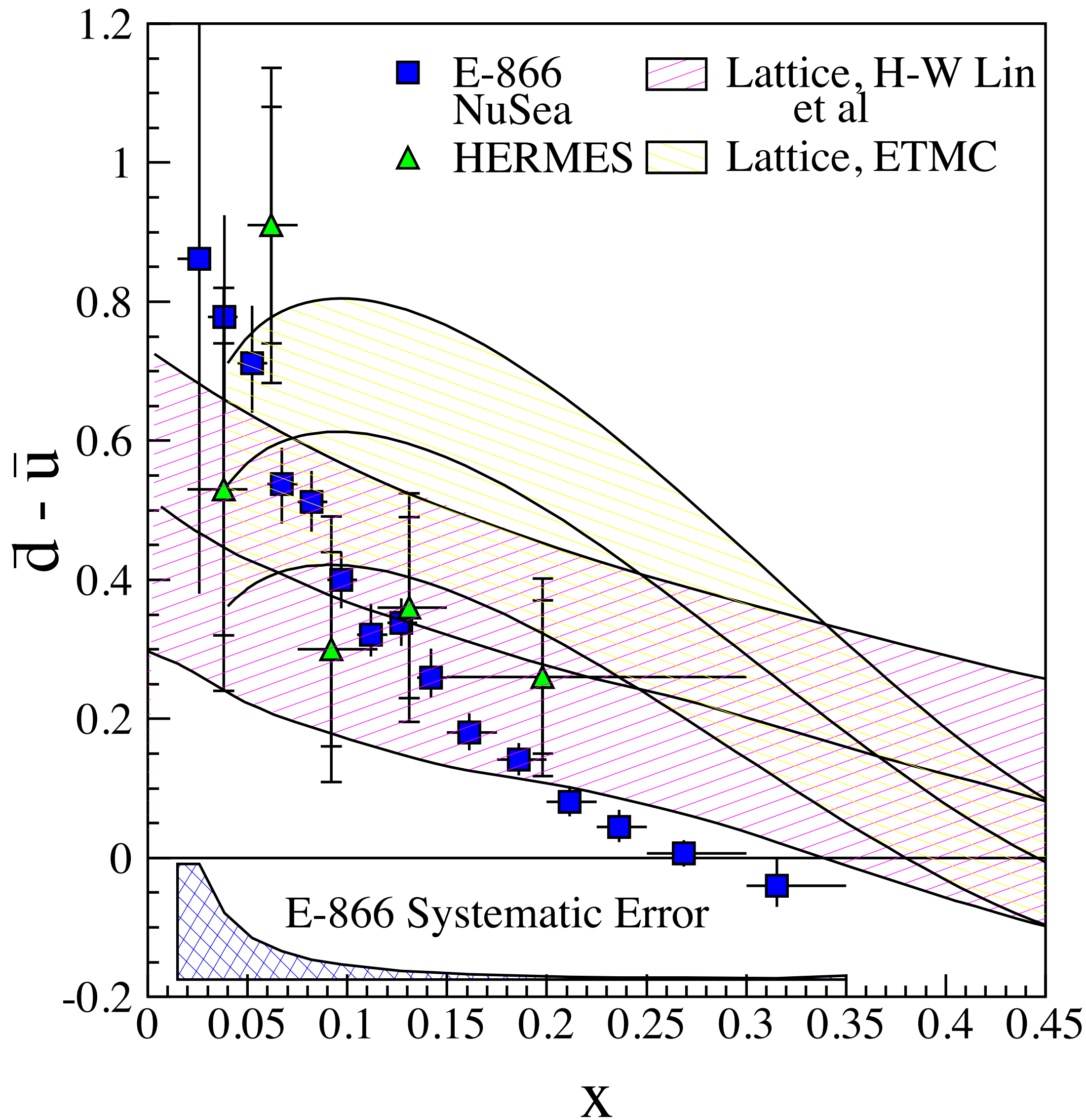
$$\bar{q}_{\mathrm{pQCD}}(x) = \bar{d}_{\mathrm{pQCD}}(x) = \bar{u}_{\mathrm{pQCD}}(x)$$

- $\bar{d}(x) - \bar{u}(x)$
  - Symmetric sea via pair production from gluons subtracts away
  - No Gluon contribution at 1st order in α_s
  - Nonperturbative models are motivated by the observed difference



Proton Structure: By What Process Is the Sea Created?

- Lattice weighs in!!



Sea Quark EMC Effect

Guggenheim, Bilbao, Spain

The European Muon Collaboration (EMC) Effect

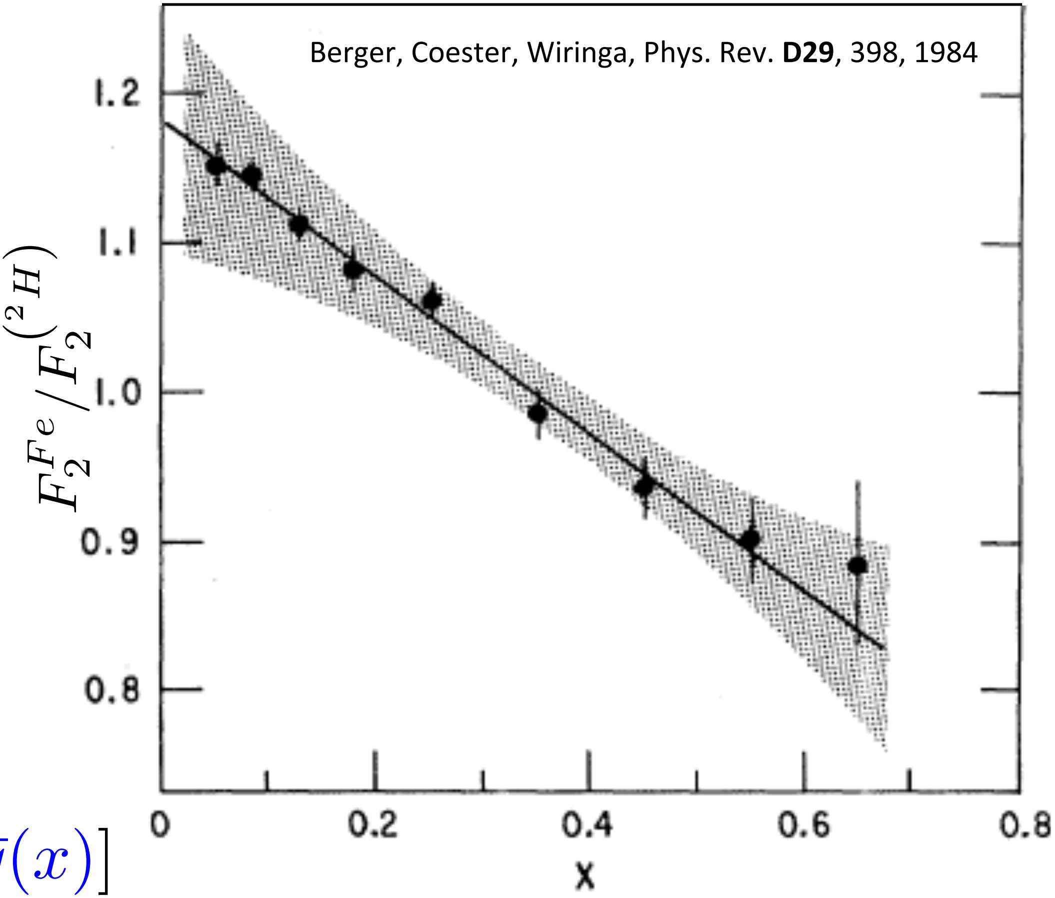
Are the parton distributions in nucleons within a nucleus the same as free nucleons?

- Is there a difference between hitting a proton in a nucleus and a free proton?
- Hard scattering makes an implicit assumption that the interaction is energetic enough so that the binding of quarks in a proton is small so surely, the binding of protons in the nucleus is also small?
- Do the quarks change configuration?

The European Muon Collaboration (EMC) Effect

Are the parton distributions in nucleons within a nucleus the same as free nucleons?

- Experimentally—No
- EMC measured the DIS F_2 ratio for Iron to Deuterium



$$F_2(x) = \sum_{q\in\{u,d\dots\}} e_q^2\left[q(x) + \bar{q}(x)\right]$$

Why?

- Shadowing
- Nuclear binding effects

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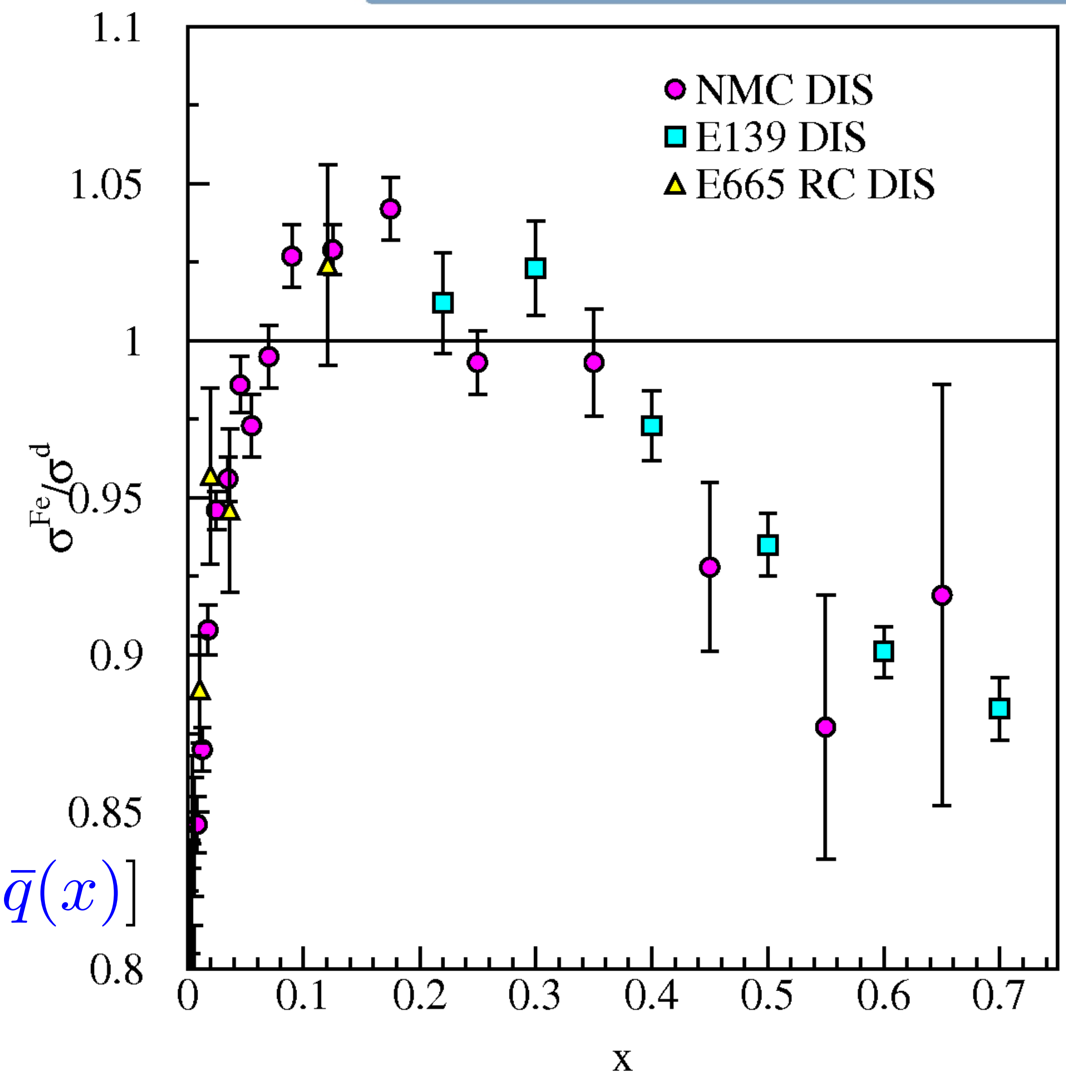
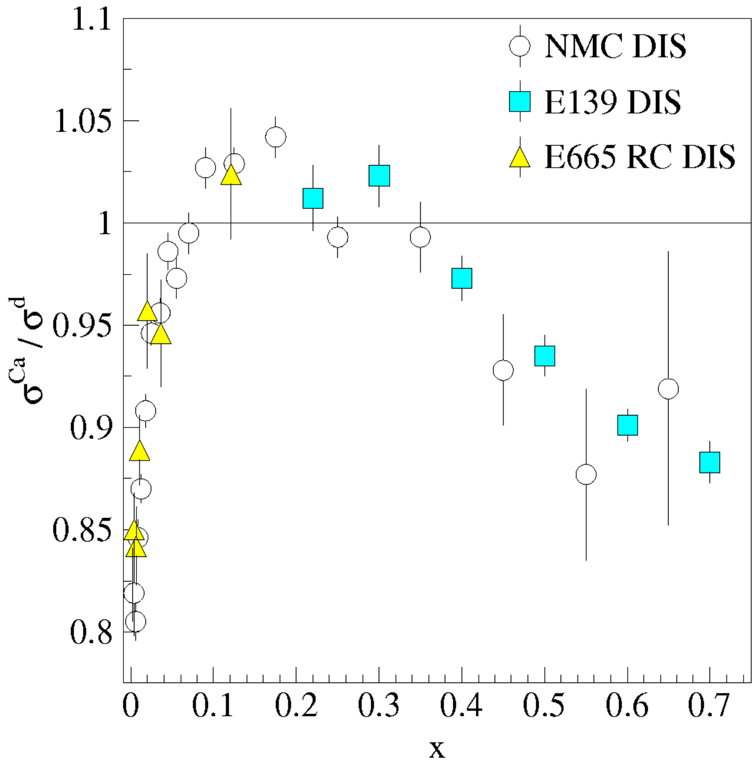
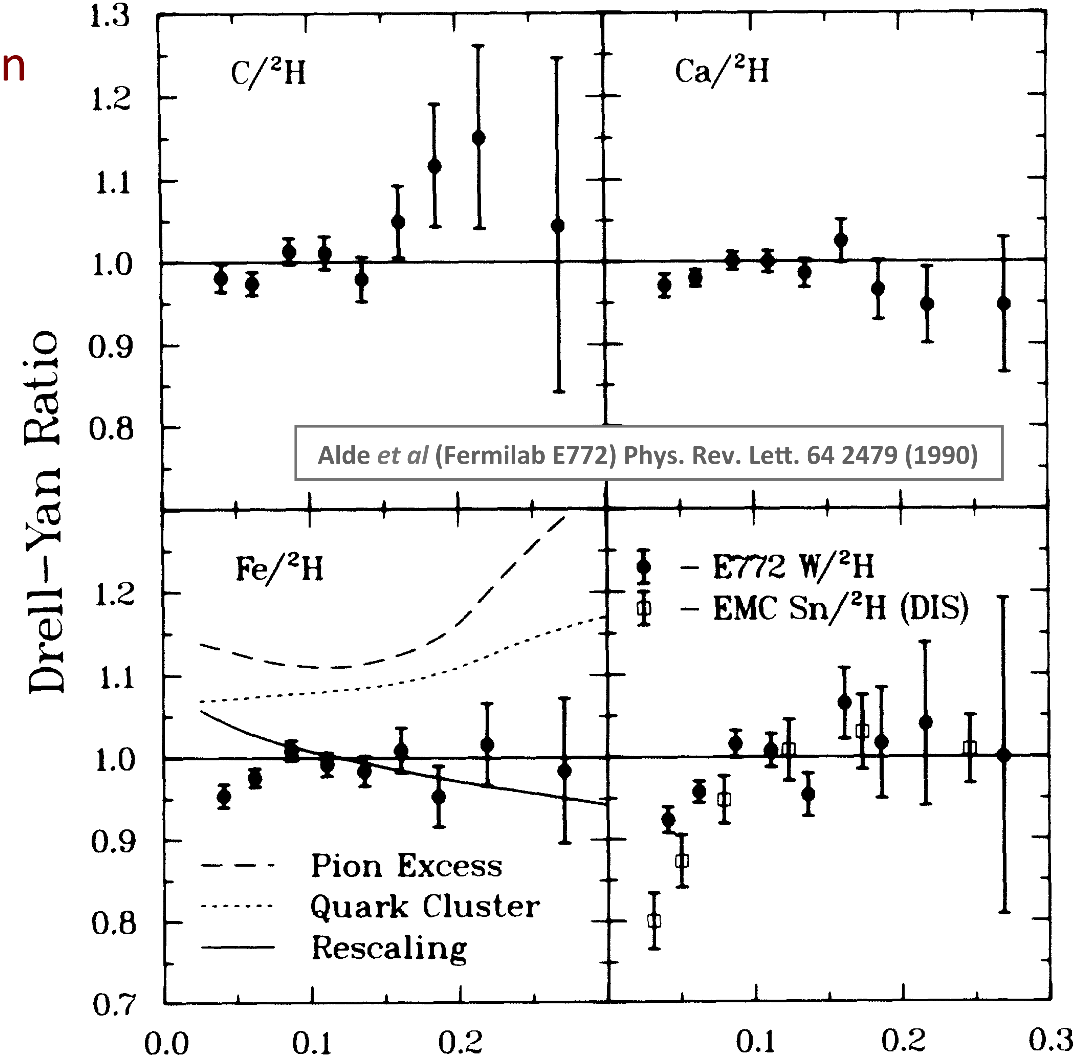


Do quarks and antiquarks experience the same modifications?

Structure of nucleonic matter: How do DIS and Drell-Yan data compare?

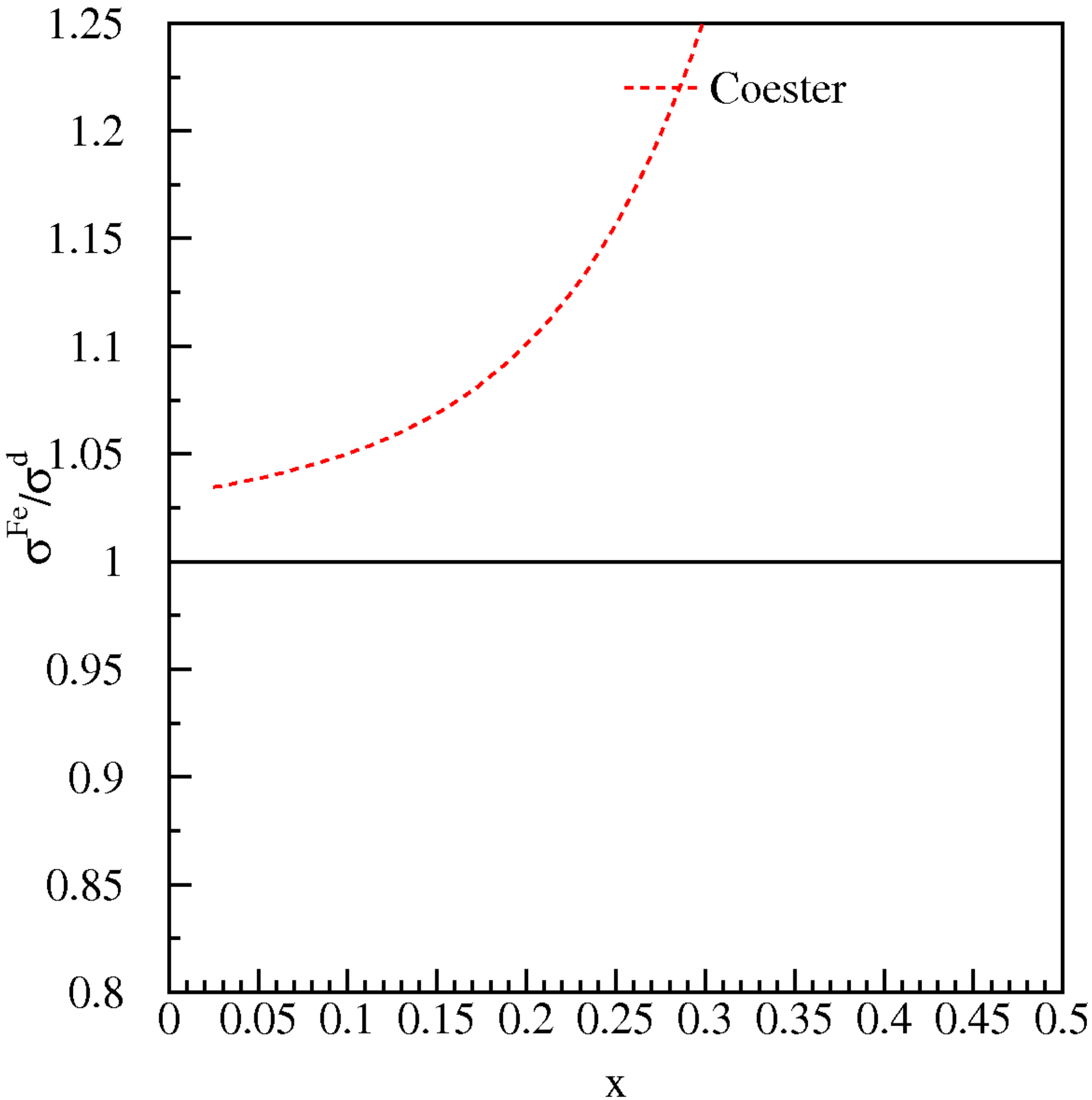
- Shadowing present in Drell-Yan
- Antishadowing not seen in Drell-Yan
  —Valence only effect





Structure of nucleonic matter: Where are the nuclear pions?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual “Nuclear” mesons.



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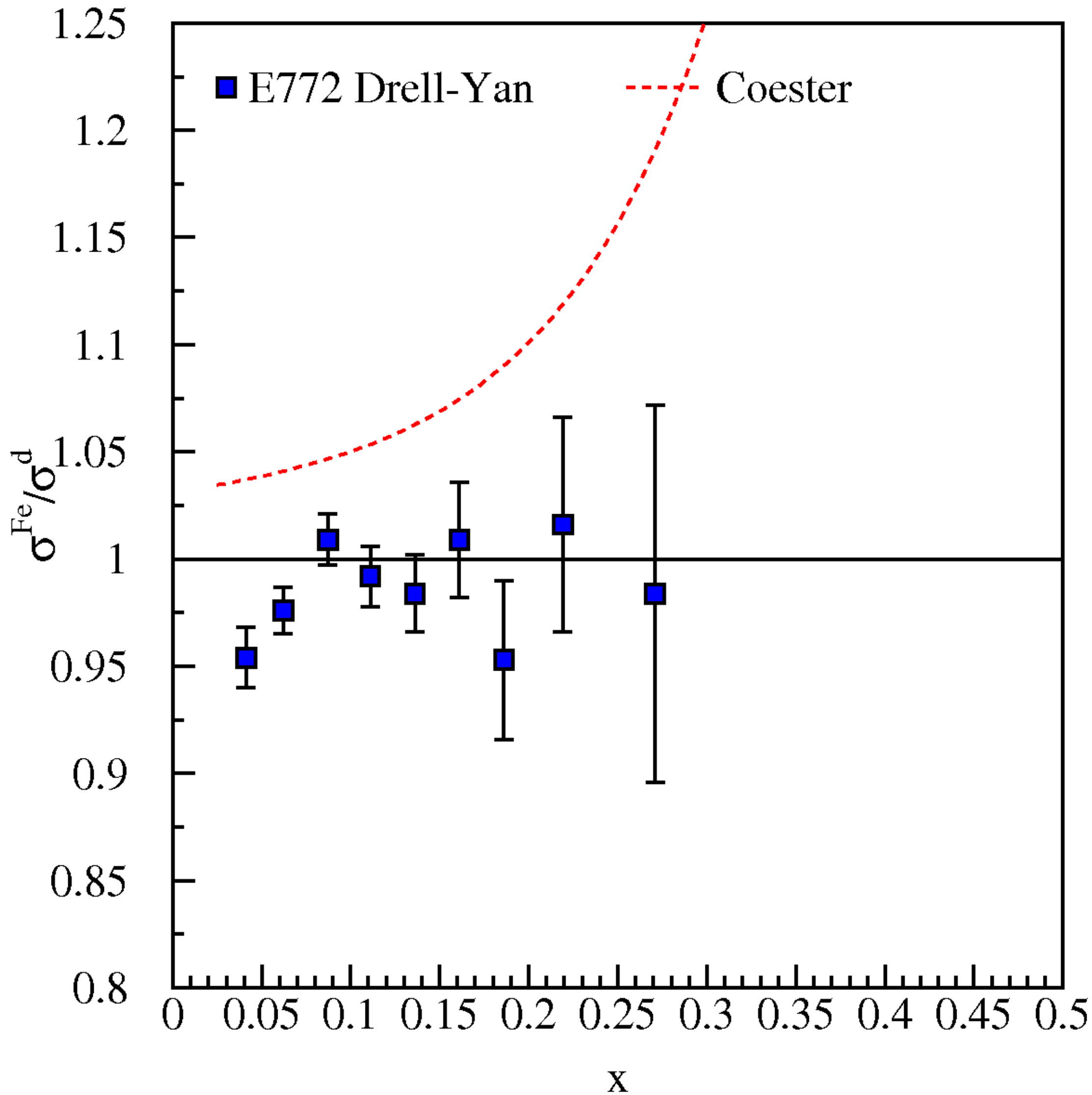
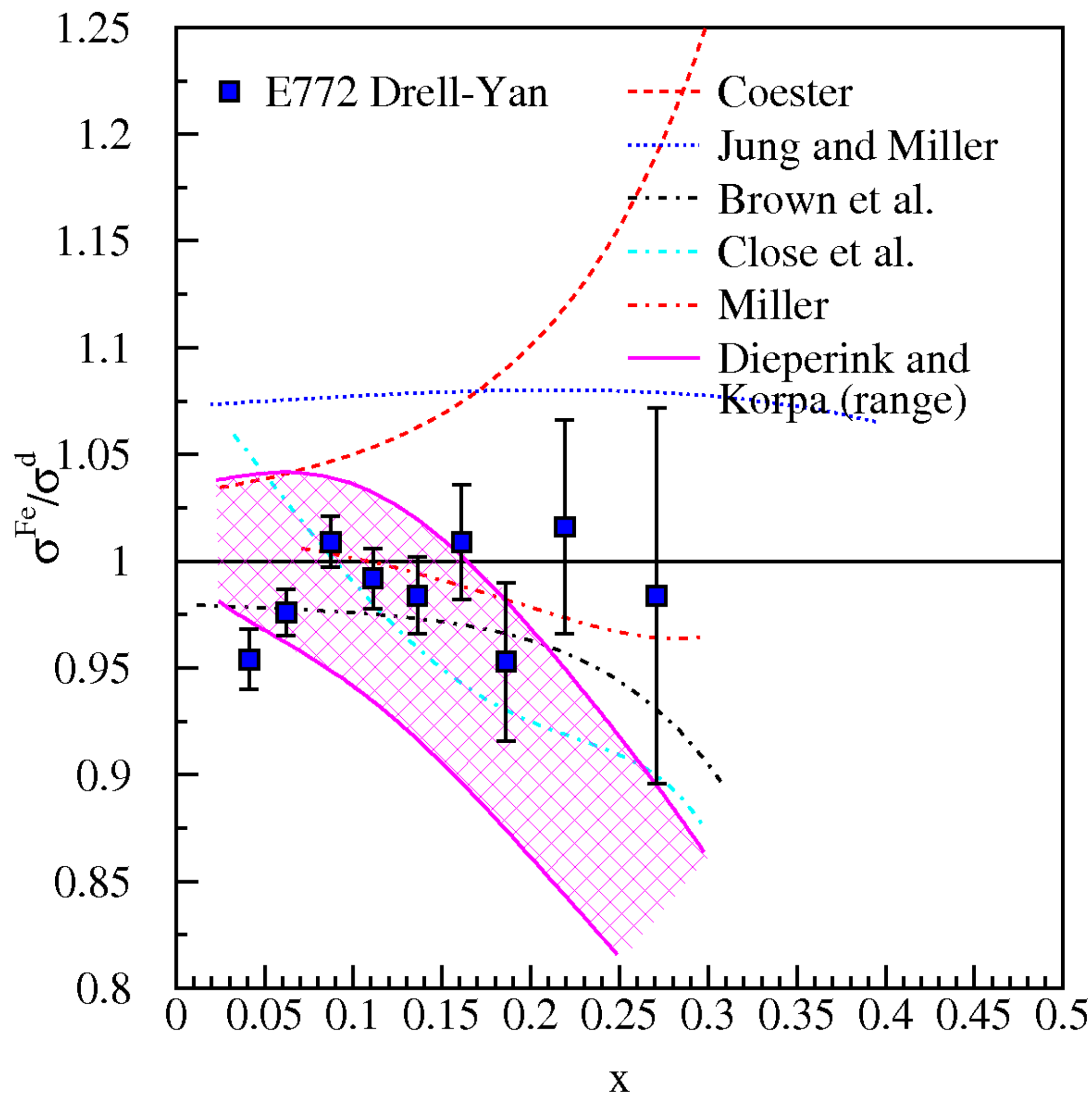


Structure of nucleonic matter: Where are the nuclear pions?

- The binding of nucleons in a nucleus is expected to be governed by the exchange of virtual "Nuclear" mesons.
- No antiquark enhancement seen in Drell-Yan (Fermilab E772) data.
- Contemporary models predict large effects to antiquark distributions as x increases.
- **Models must explain both DIS-EMC effect and Drell-Yan**



Exploring the Sea

How can we measure the sea distributions?

Need a process that can isolate sea contributions:

- SIDIS
  - Low statistics
  - K/π identification
  - Knowledge of fragmentation functions (D^π)
  - HERMES, COMPASS, JLab 12 GeV

$$N^{\pi^\pm} \propto \sum_{q\in\{u,d,\dots\}} \left[q(x,Q^2)D^{\pi^\pm} + \bar{q}(x,Q^2)D^{\pi^\pm}\right]$$

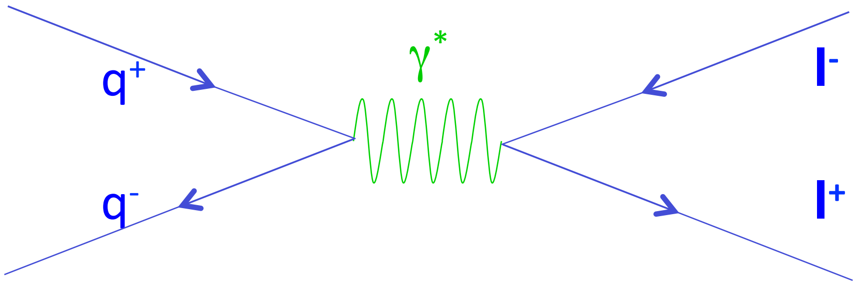
- Collider W production
  - Fermilab Tevatron, CERN LHC

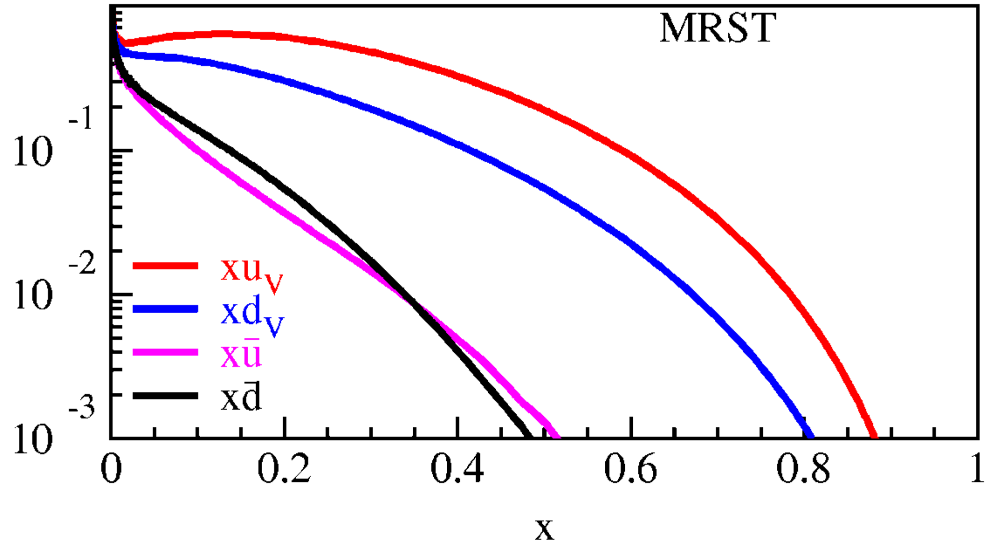
$$A_W(y) \propto \frac{u(x_1)\bar{d}(x_2) - d(x_1)\bar{u}(x_2)}{u(x_1)\bar{d}(x_2) + d(x_1)\bar{u}(x_2)}$$

- Drell-Yan
  - Rest of this talk

$$\frac{d\sigma}{dx_1 dx_2} \propto \sum_{q\in\{u,d,\dots\}} e_q^2 \left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\right]$$

Drell-Yan Cross Section

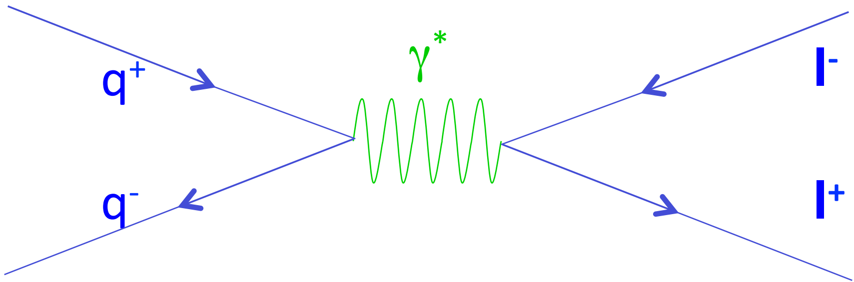


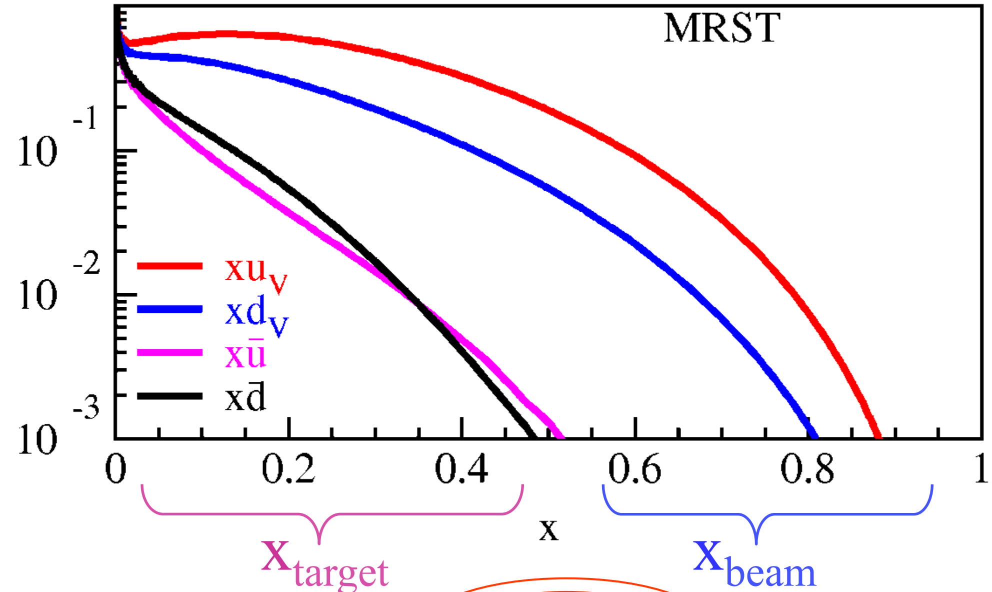


- Cross section is a convolution of beam and target parton distributions

$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t)\right]$$

Drell-Yan Cross Section





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Acceptance limited

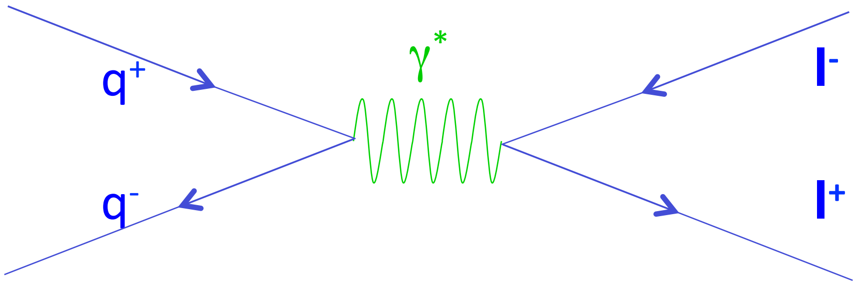
(Fixed Target, Hadron Beam)

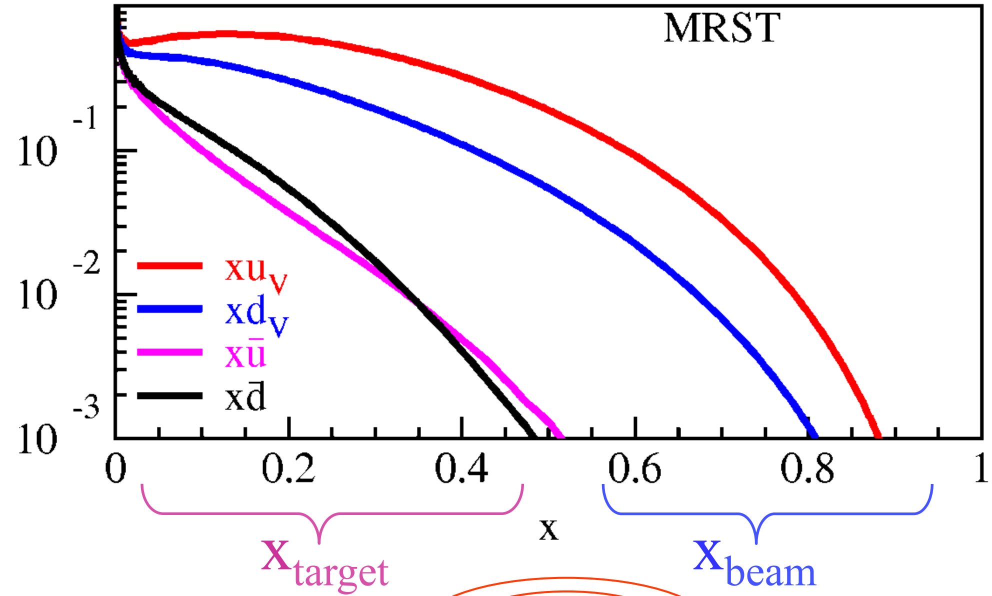
- u-quark dominance

  $(2/3)^2$ vs. $(1/3)^2$

Beam	Sensitivity	Experiment
Hadron	Beam quarks target antiquarks	Fermilab, J-PARC RHIC (forward acpt.)
Anti-Hadron	Beam antiquarks Target quarks	J-PARC, GSI-FAIR Fermilab Collider
Meson	Beam antiquarks Target quarks	COMPASS, J-PARC

Drell-Yan Cross Section





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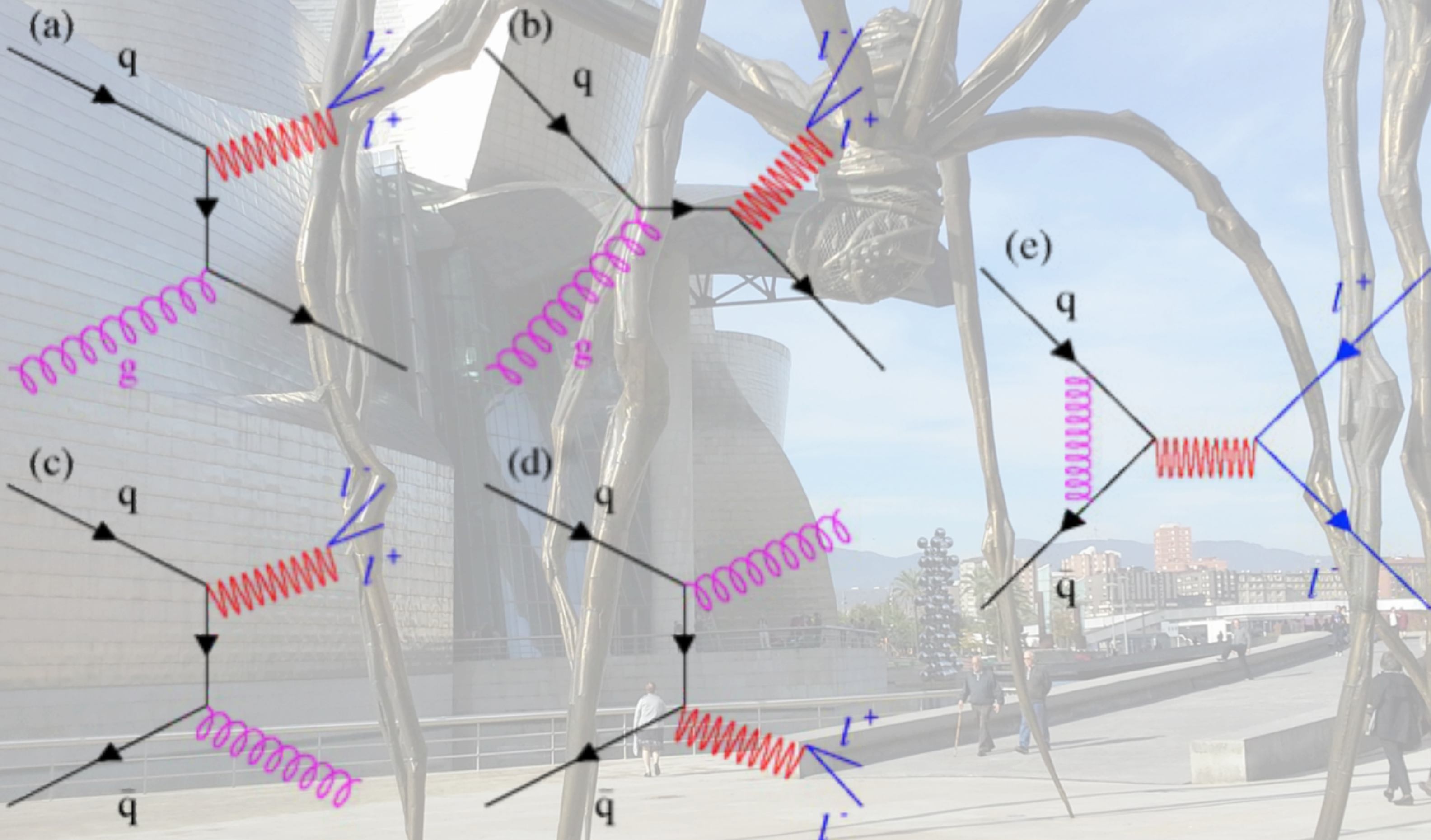
$$\frac{\sigma^{\mathrm{pd}}}{2\sigma^{\mathrm{pp}}} = \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right]$$

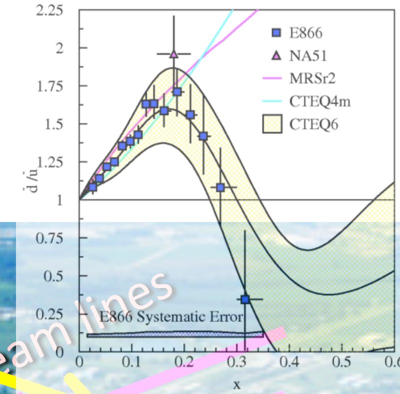
Beam	Sensitivity	Experiment
Hadron	Beam quarks target antiquarks	Fermilab, J-PARC RHIC (forward acpt.)

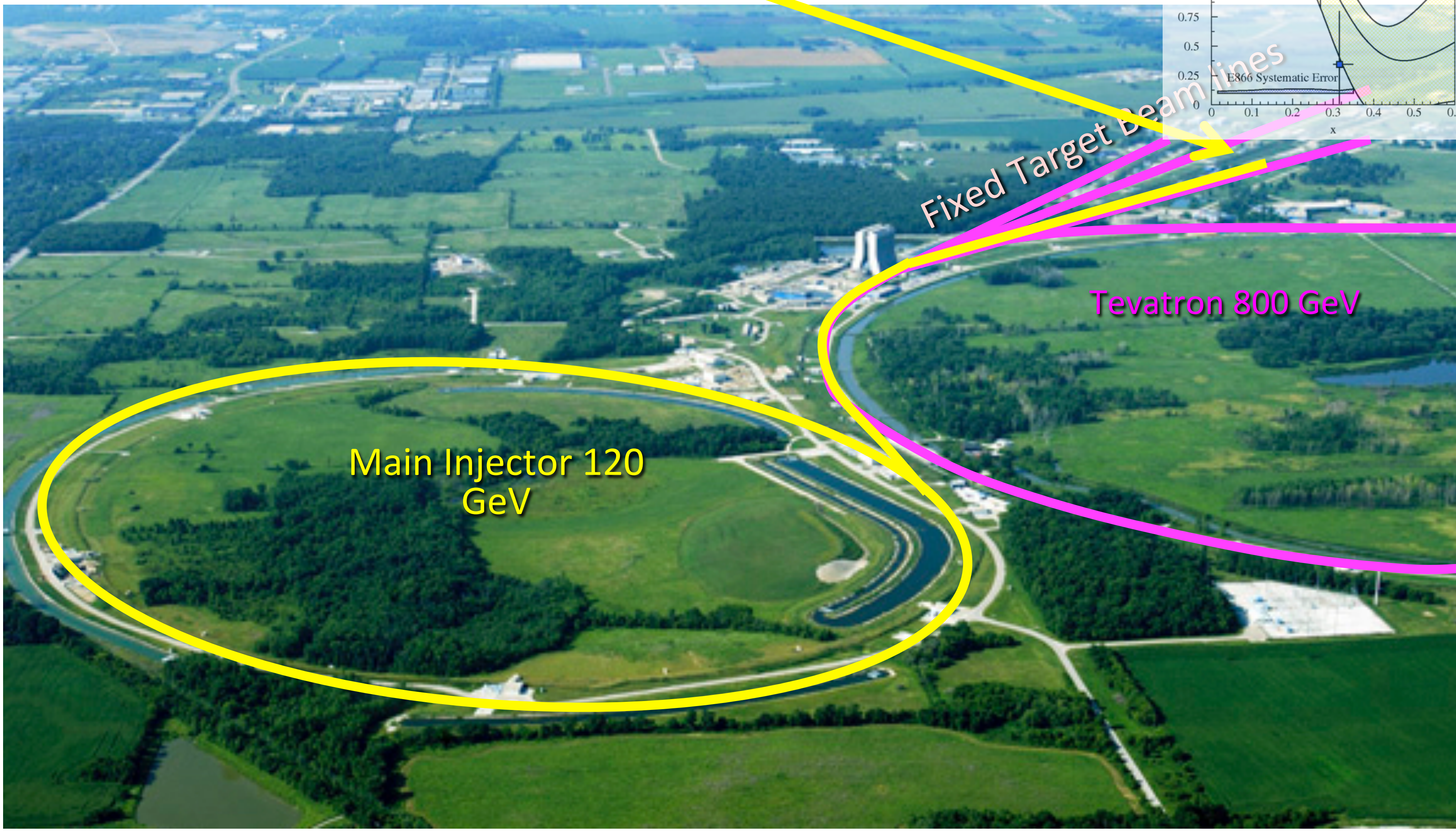
Drell-Yan Cross Section—Next-to-leading order α_s

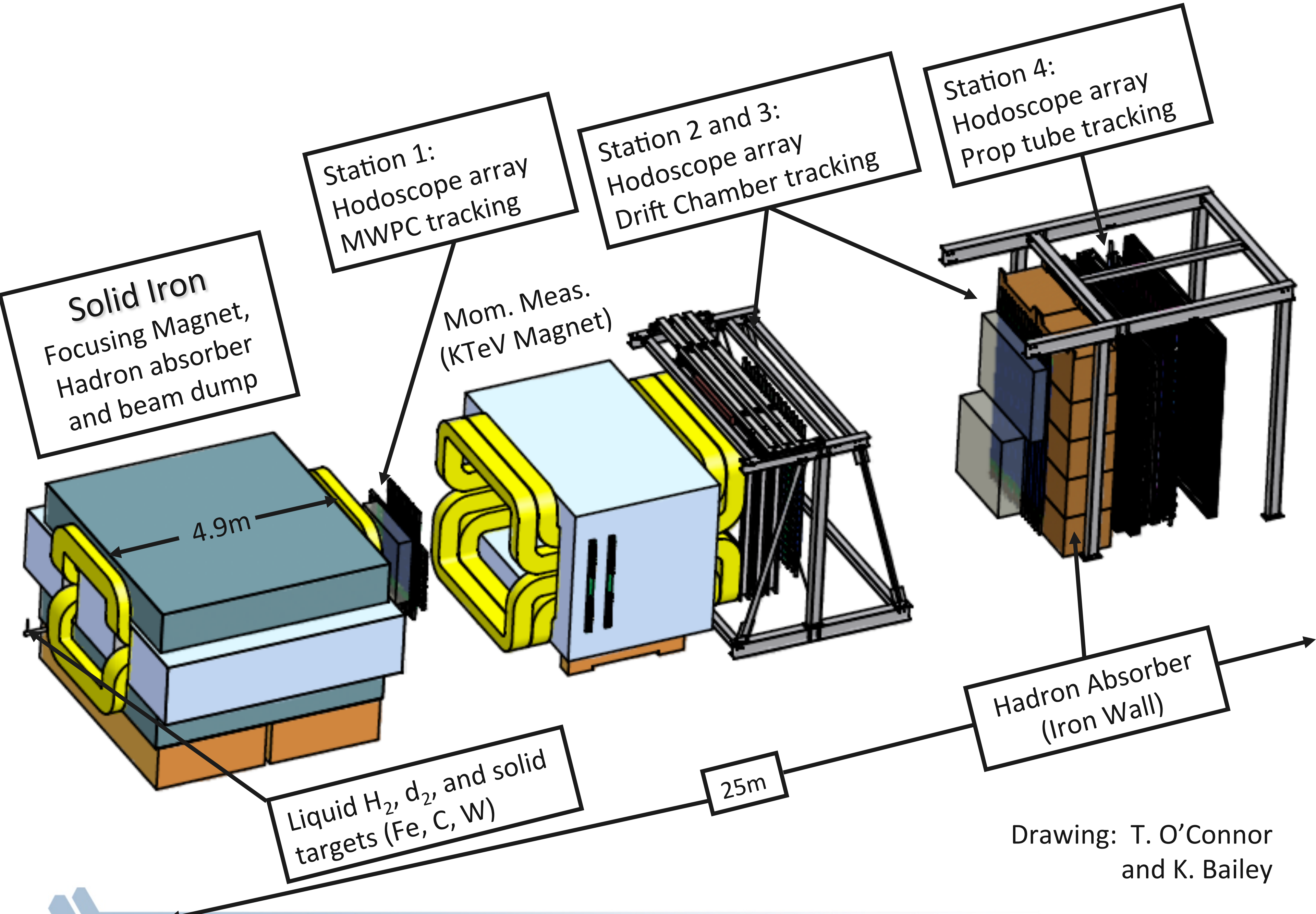
- These diagrams are responsible for approximately 50% of the measured cross section



SeaQuest Experiment



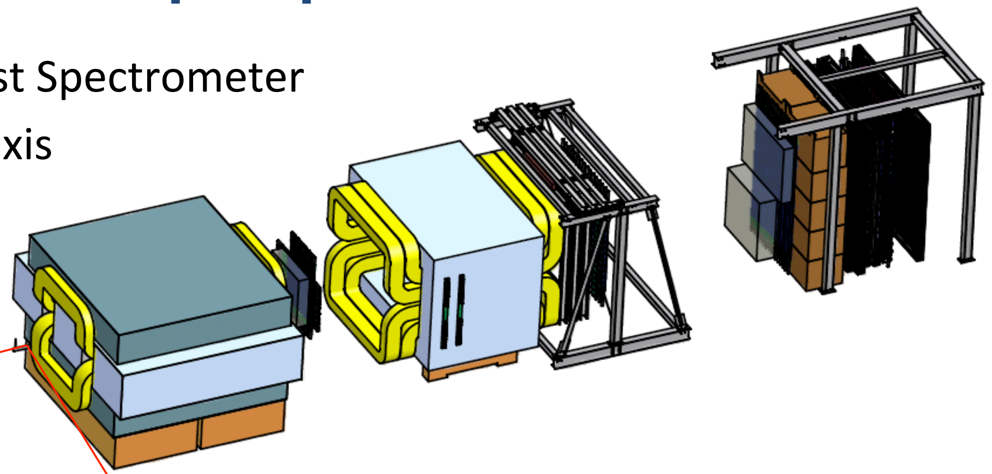


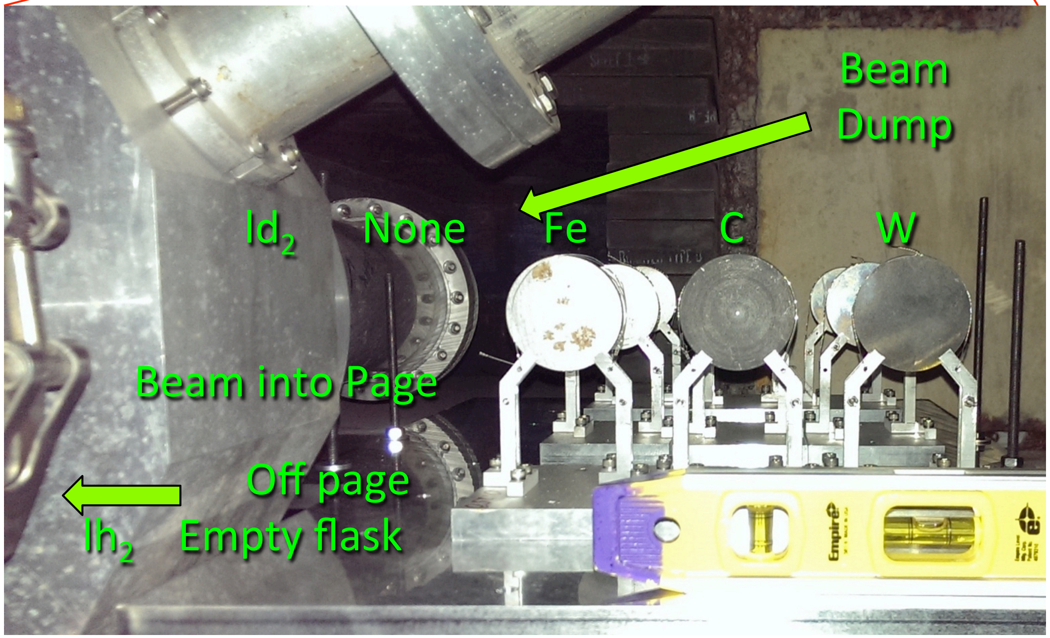


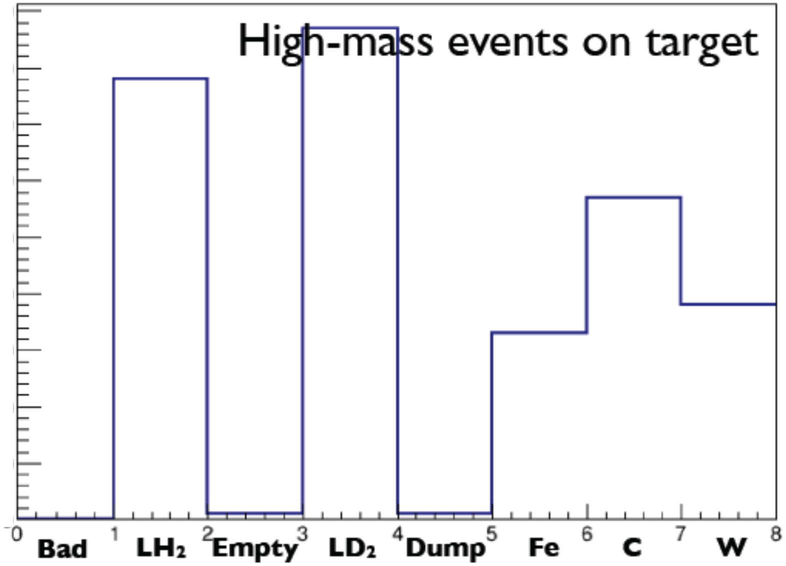
Drawing: T. O'Connor and K. Bailey

Data From FY2014—target-dump separation

- Entire beam interacts upstream of SeaQuest Spectrometer
- Pointing resolution very poor along beam axis







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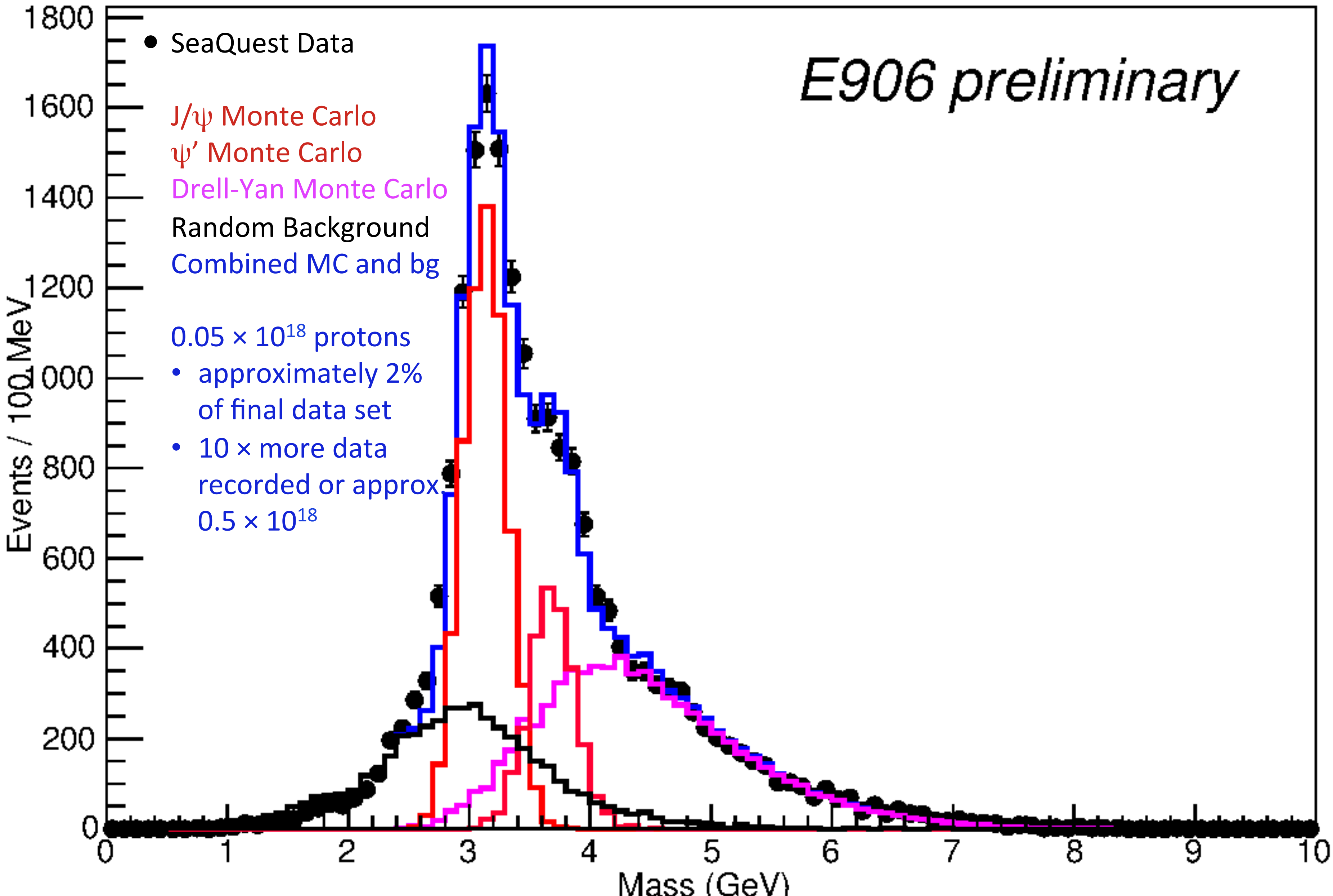
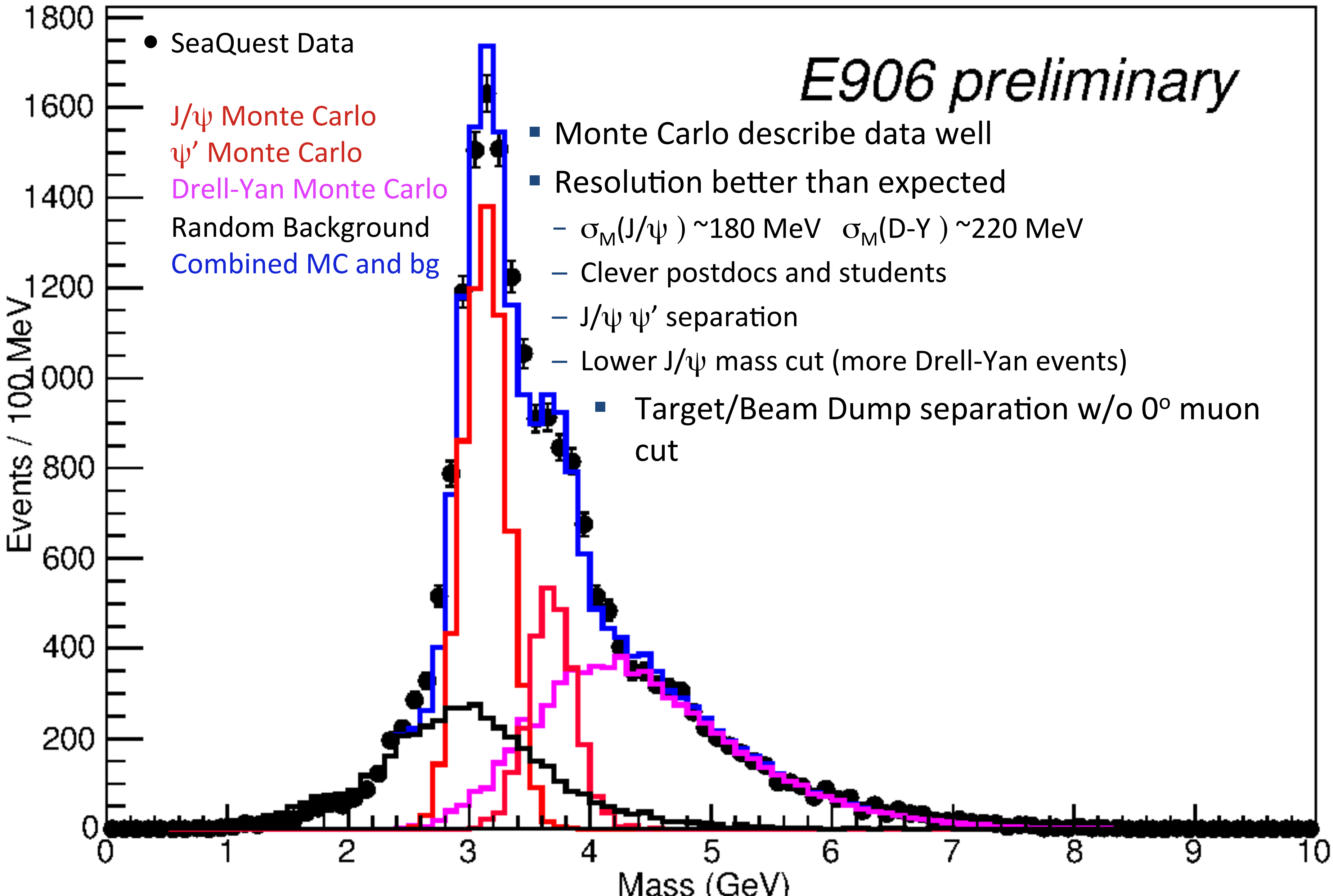
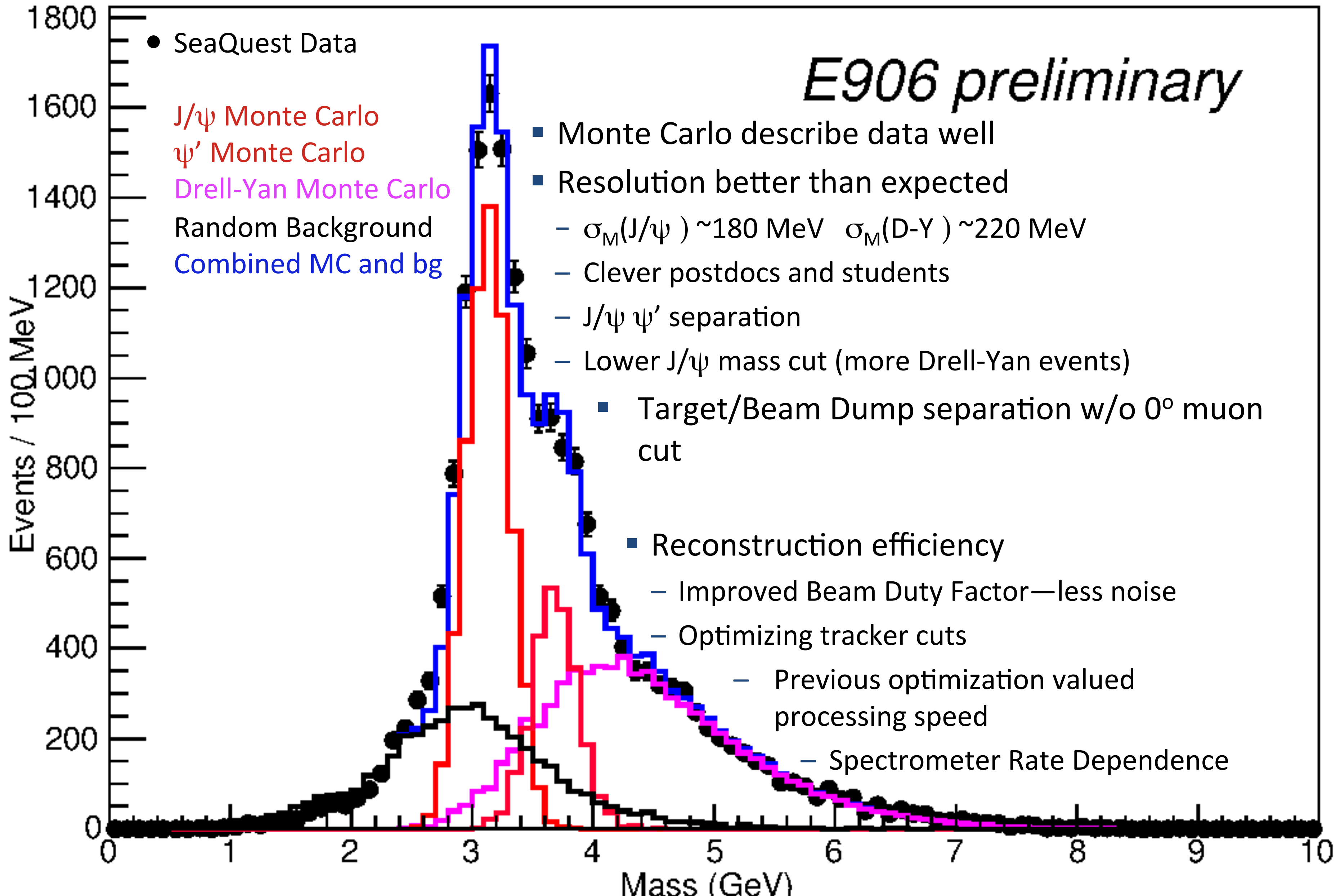


Data From FY2014



- Monte Carlo describe data well
- Resolution better than expected
  - σ_M(J/ψ) ~180 MeV σ_M(D-Y) ~220 MeV
  - Clever postdocs and students
  - J/ψ ψ' separation
  - Lower J/ψ mass cut (more Drell-Yan events)
    - Target/Beam Dump separation w/o 0^o muon cut

Data From FY2014



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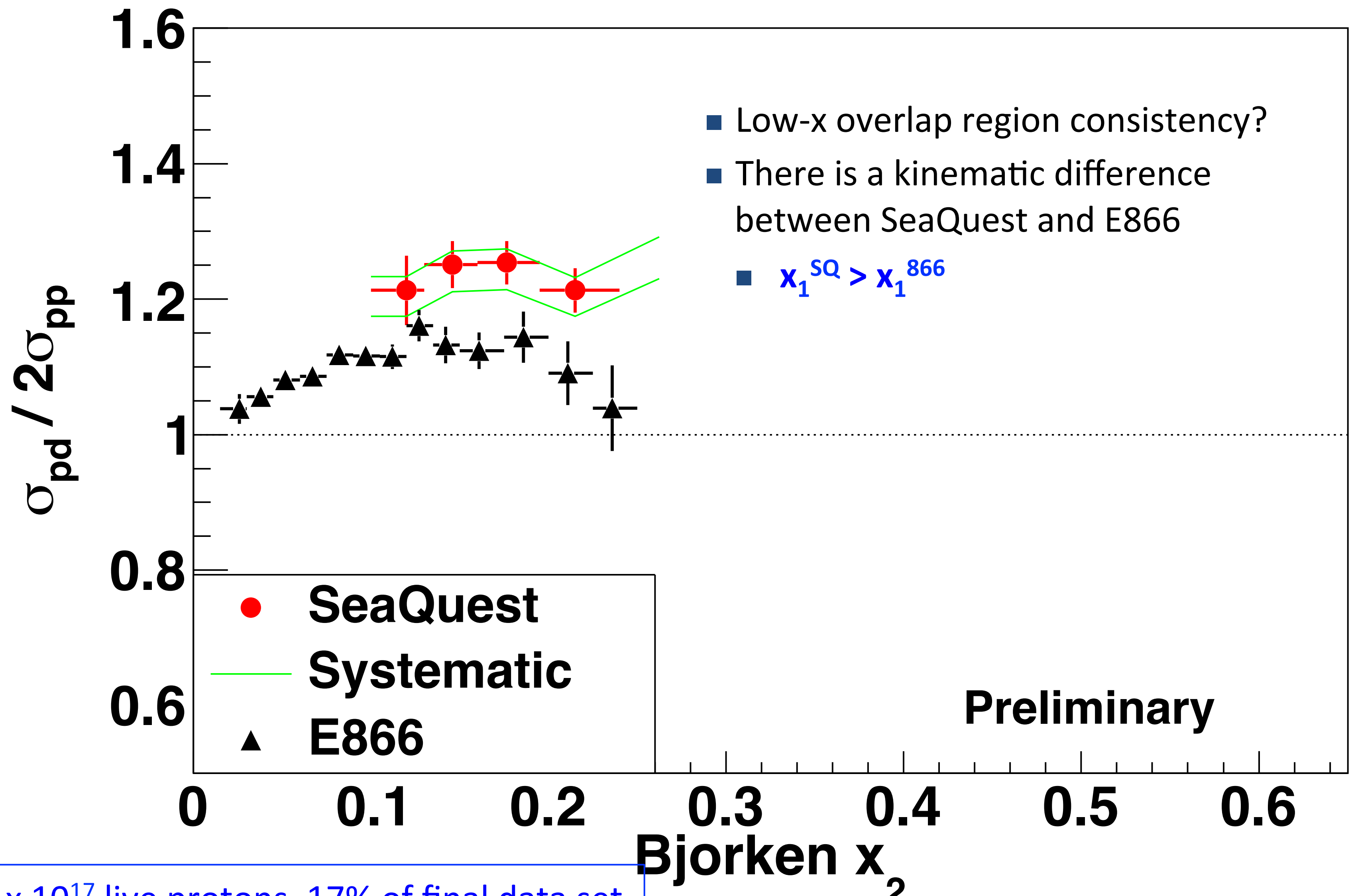
  - Lower J/ψ mass cut (more Drell-Yan events)
- Target/Beam Dump separation w/o 0° muon cut
- Reconstruction efficiency
  - Improved Beam Duty Factor—less noise
  - Optimizing tracker cuts
    - Previous optimization valued processing speed
  - Spectrometer Rate Dependence

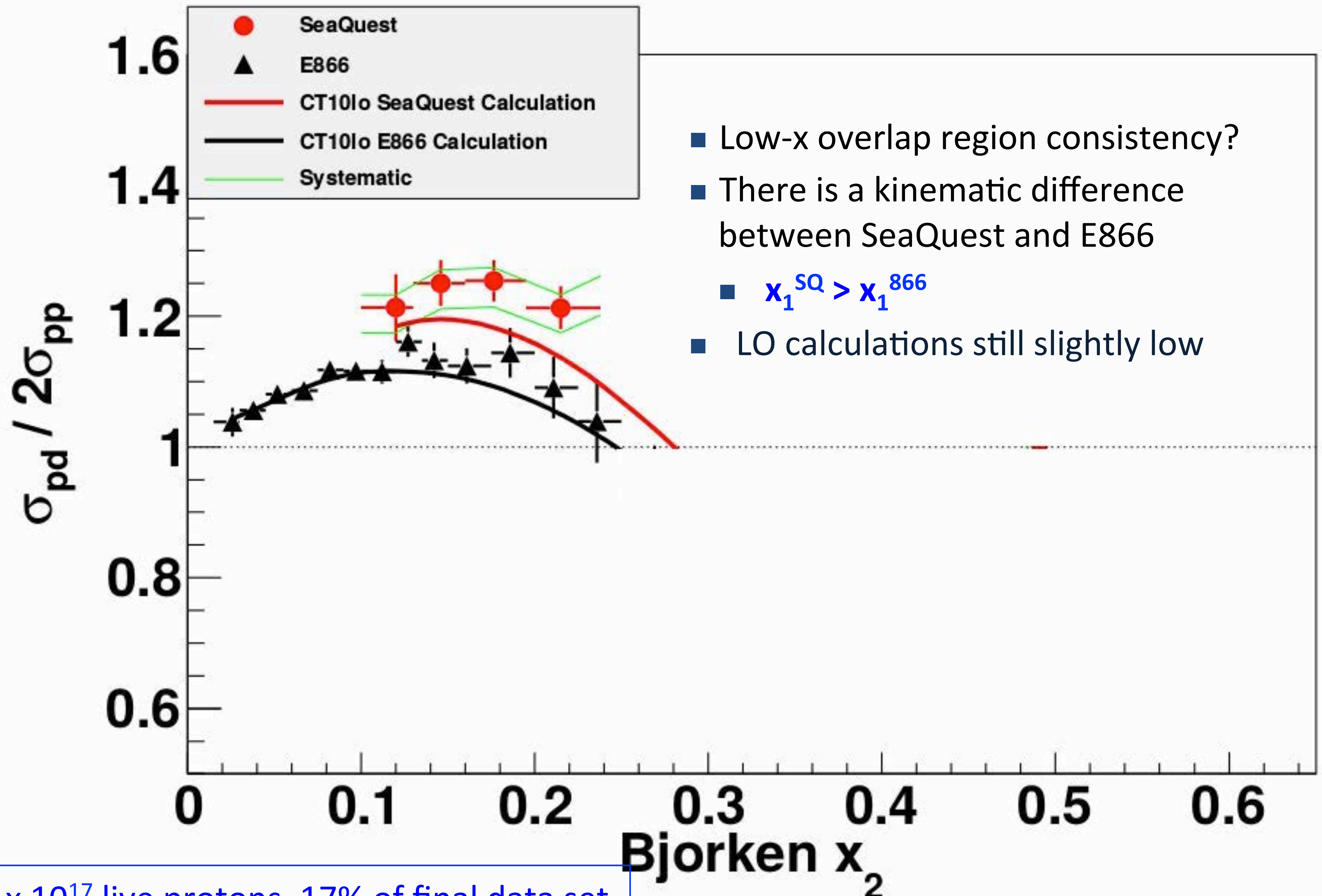
SeaQuest Cross Section Ratio



- Low-x overlap region consistency?
- There is a kinematic difference between SeaQuest and E866
  - $x_1^{SQ} > x_1^{866}$

3.5 x 10^{17} live protons, 17% of final data set

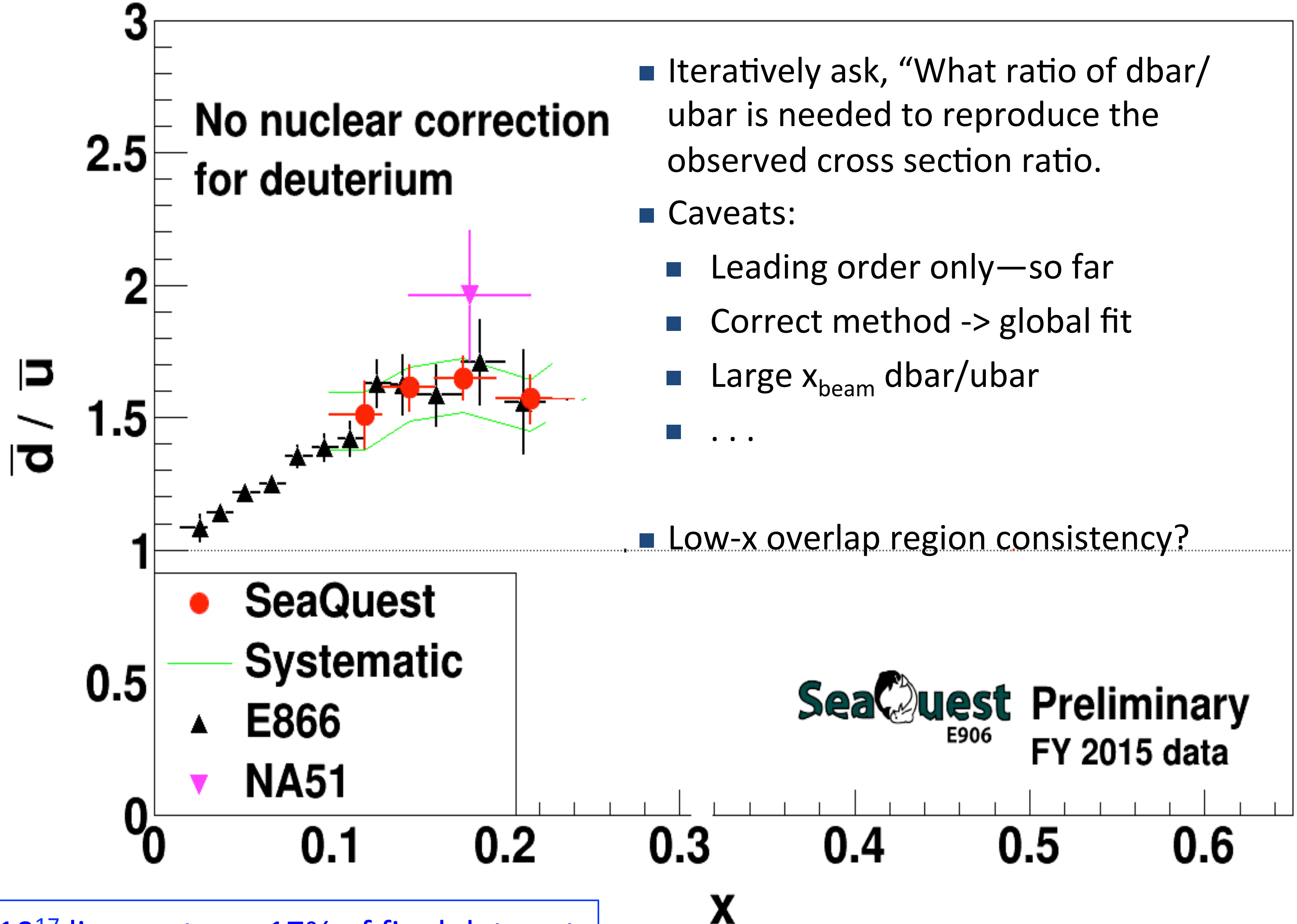
SeaQuest Cross Section Ratio



- Low-x overlap region consistency?
- There is a kinematic difference between SeaQuest and E866
  - $x_1^{SQ} > x_1^{866}$
- LO calculations still slightly low

3.5 x 10^{17} live protons, 17% of final data set

SeaQuest LO dbar/ubar extraction



- Iteratively ask, "What ratio of dbar/ ubar is needed to reproduce the observed cross section ratio.
- Caveats:
  - Leading order only—so far
  - Correct method -> global fit
  - Large x_{beam} dbar/ubar
  - . . .
- Low-x overlap region consistency?

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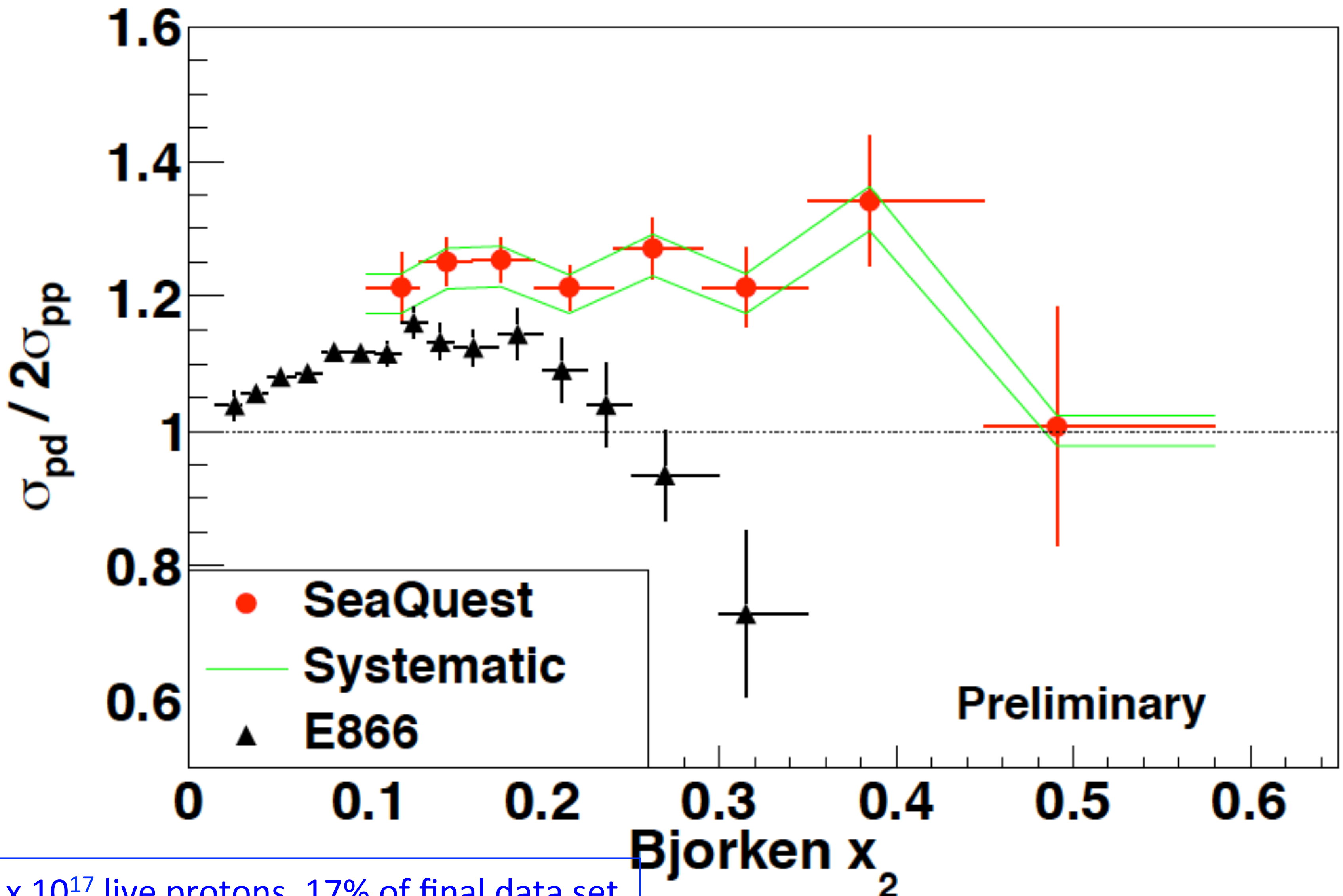
SeaQuest Cross Section Ratio



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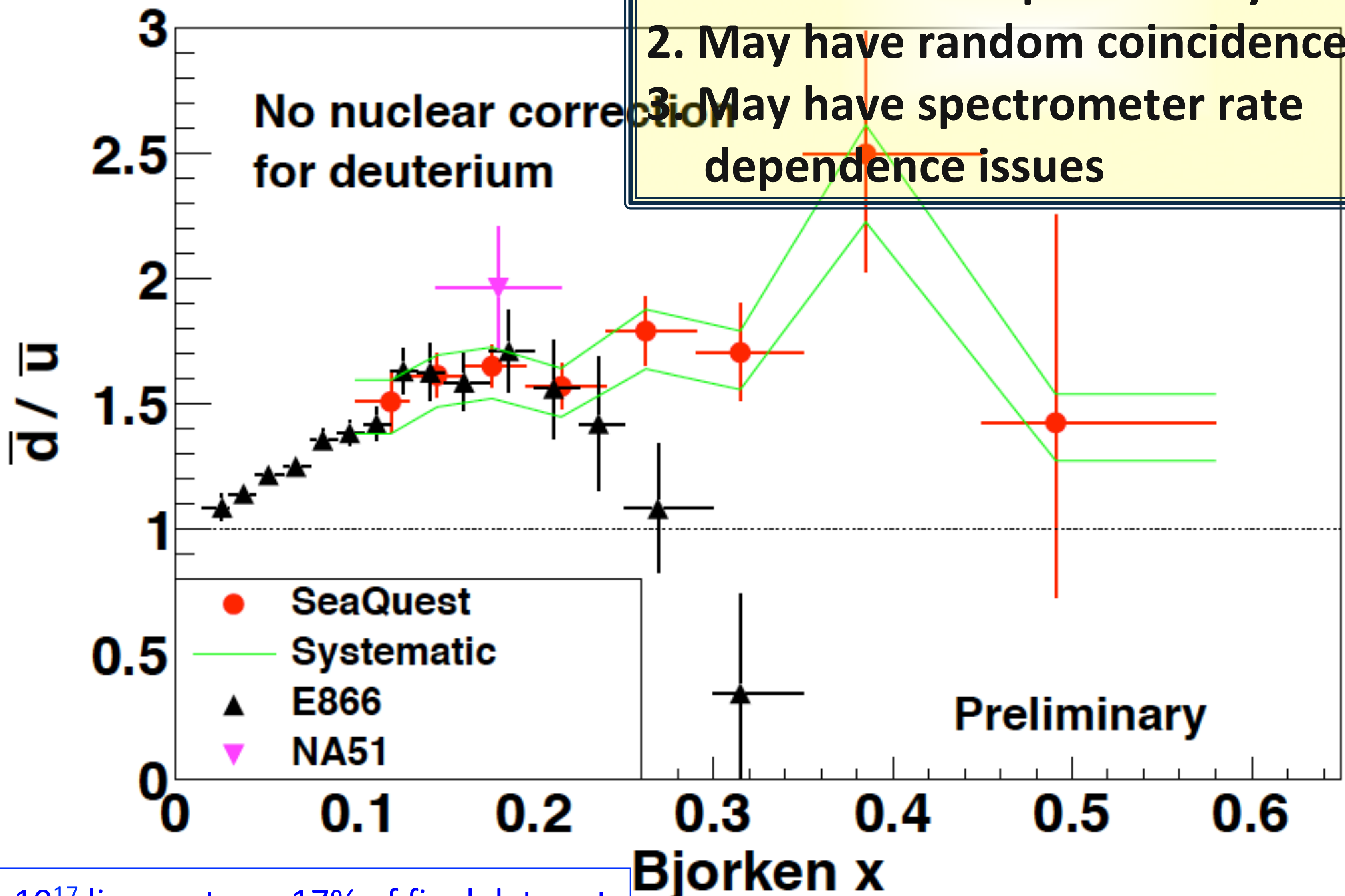
SeaQuest Cross Section Ratio and dbar/ubar

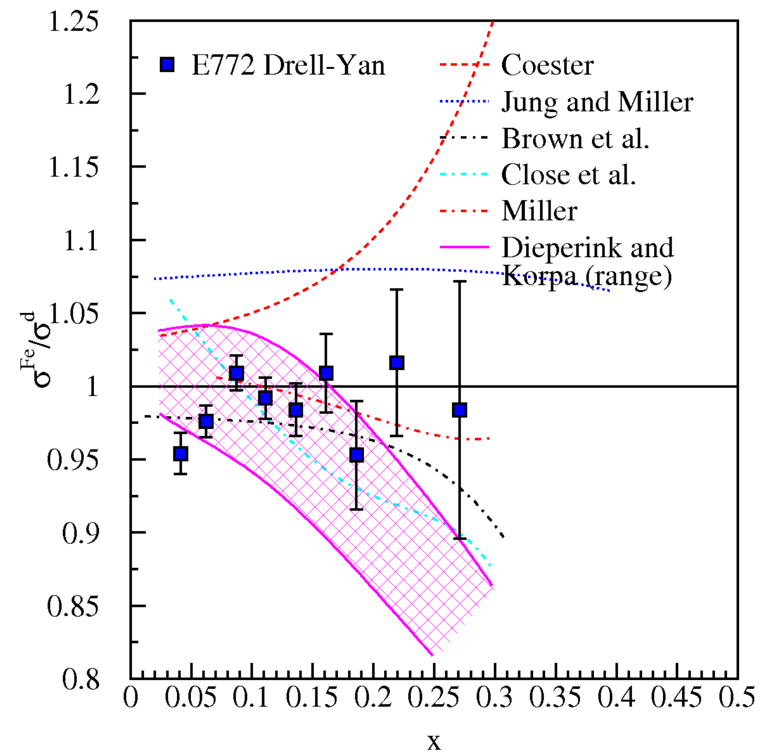
Caveat emptor:
1. These data are preliminary
2. May have random coincidences
3. May have spectrometer rate dependence issues

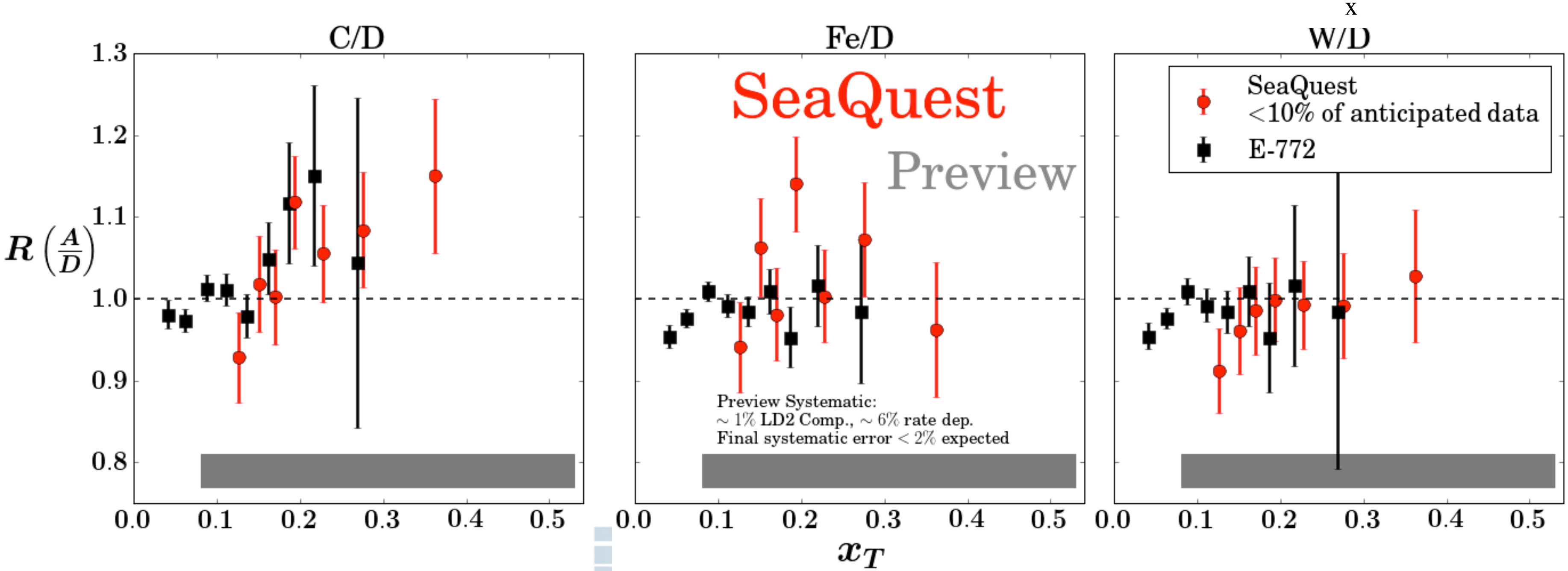


3.5 x 10^{17} live protons, 17% of final data set

SeaQuest Seaquark EMC Effect

- Data Presented by Bryan Dannowitz April 2015 APS
- No antiquark enhancement apparent.
- 10% of anticipated statistical precision
- Increased detector acceptance at large-x to come.





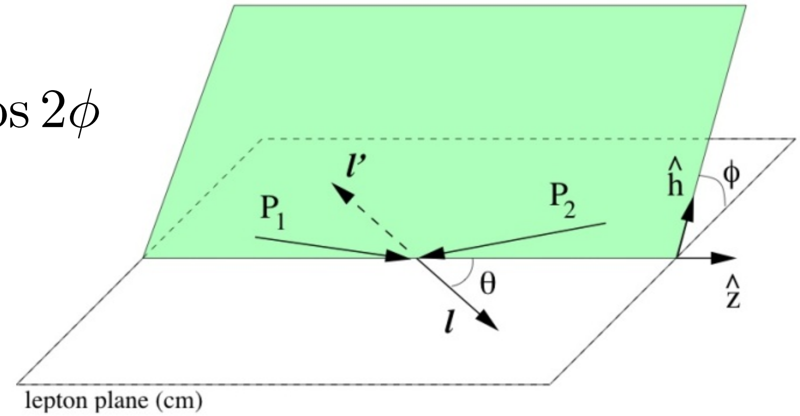
Now add Spin

- Dynamics make things messy
- . . . Or more interesting?

Leading order Single Spin Drell-Yan Cross Section

Formula: from Aram Kotzinian
Slide: content from Oleg Denisov

$$
\begin{aligned}
\frac{d\sigma^{\mathrm{LO}}}{d^4q\,d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_{\mathrm{U}}^{\mathrm{LO}} \Big[1 &+ D_{\sin^2\theta}^{\mathrm{LO}} A_{\mathrm{U}}^{\cos 2\phi} \cos 2\phi \\
&+ S_{\mathrm{L}} D_{\sin^2\theta}^{\mathrm{LO}} A_{\mathrm{L}}^{\sin 2\phi} \sin 2\phi \\
&+ \left|\vec{S}_{\mathrm{T}}\right| A_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}} \sin\phi_{\mathrm{S}} \\
&+ \left|\vec{S}_{\mathrm{T}}\right| D_{\sin^2\theta}^{\mathrm{LO}} A_{\mathrm{T}}^{\sin(2\phi+\phi_{\mathrm{S}})} \sin(2\phi+\phi_{\mathrm{S}}) \\
&+ \left|\vec{S}_{\mathrm{T}}\right| D_{\sin^2\theta}^{\mathrm{LO}} A_{\mathrm{T}}^{\sin(2\phi-\phi_{\mathrm{S}})} \sin(2\phi-\phi_{\mathrm{S}}) \Big]
\end{aligned}
$$



$A_{\mathrm{U}}^{\cos 2\phi}$ Boer-Mulders of target hadron

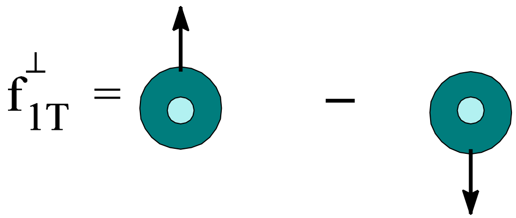
$A_{\mathrm{T}}^{\sin\phi_S}$ Sivers for beam nucleon

$A_{\mathrm{T}}^{\sin(2\phi+\phi_S)}$ Boer-Mulders of target and $h_1^{\perp}$ and pretzelosity of beam

$A_{\mathrm{T}}^{\sin(2\phi-\phi_S)}$ Boer-Mulders of target and h_1 and transversity of beam
(with polarized beam and unpolarized target)

Sivers Function and the Spin Crisis

- Correlation between unpolarized quarks and a nucleon's transverse polarization



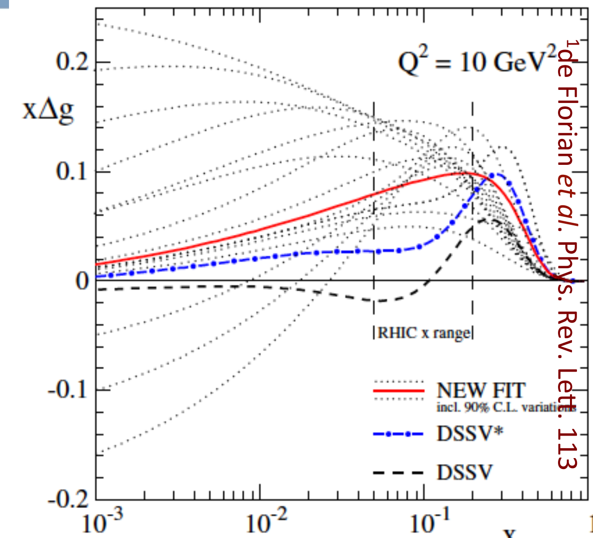
- Non-zero Sivers distribution ⇨ non-zero quark orbital momentum

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

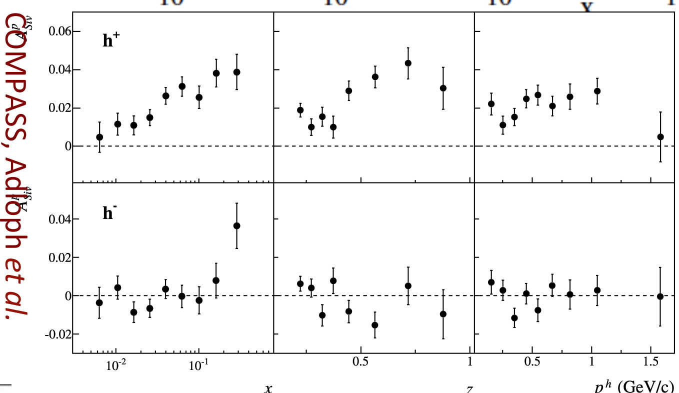
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

½ ΔΣ ≈ 25% ΔG ≈ 0-15%[1]

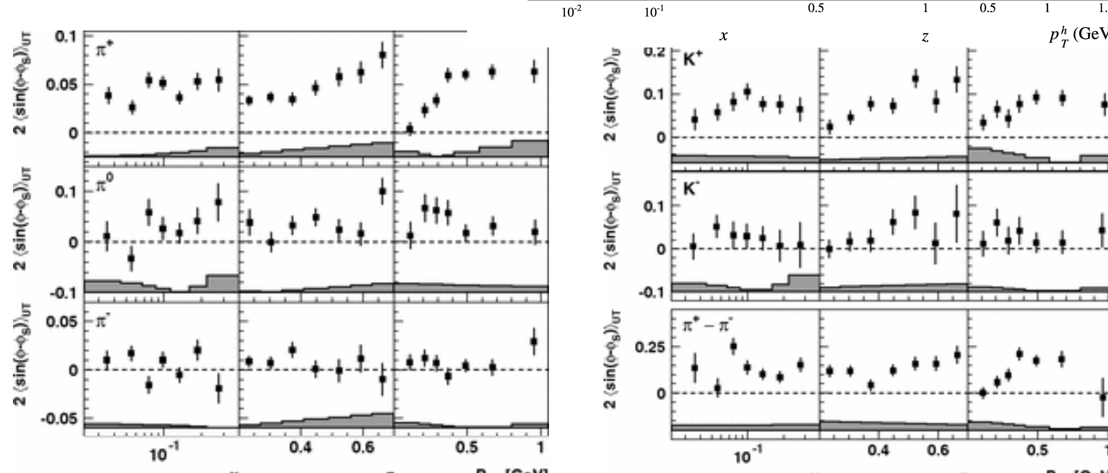
L ≈ unmeasured



[1]de Florian *et al.* Phys. Rev. Lett. 113



COMPASS, Adolph *et al.* Phys Lett. B, 717, 383

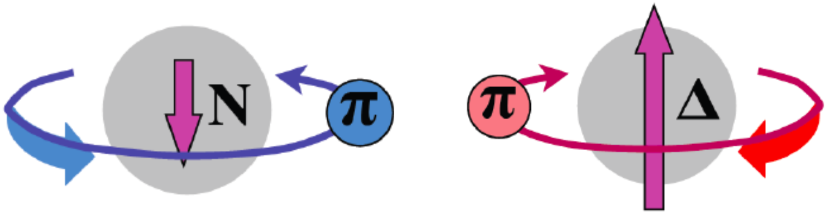


HERMES, Airapetian *et al.* Phys. Rev. Lett. 103, 152002

Pion Cloud and OAM

- Consider a nucleonic pion cloud
  $|p\rangle = |p_0\rangle + |N\pi\rangle + |\Delta\pi\rangle + \ldots$

  Pions $J^p=0^-$ Negative Parity
  Need L=1 to get proton's $J^p=\frac{1}{2}^+$



Sea quarks should carry orbital angular momentum.

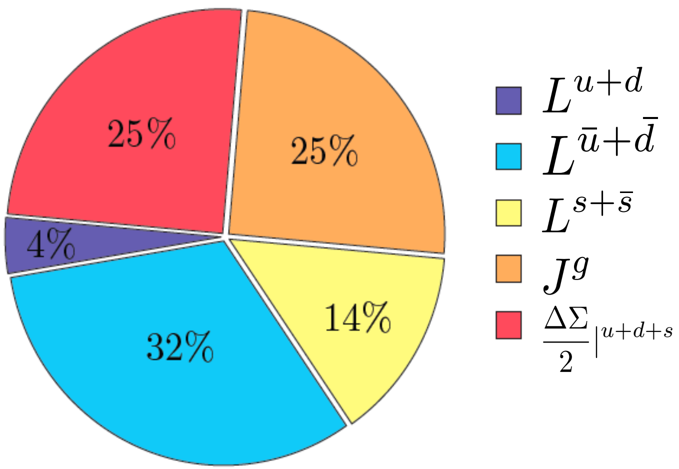
How measure quark OAM ?

- GPD: Generalized Parton Distribution
- TMD Transverse Momentum Distribution

$$A_N = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \stackrel{?}{=} 0$$

$$A_N^{DY} \propto \frac{u(x_b)\cdot f_{1T}^{\perp,\bar{u}}(x_t)}{u(x_b)\cdot \bar{u}(x_t)}$$

Lattice QCD:



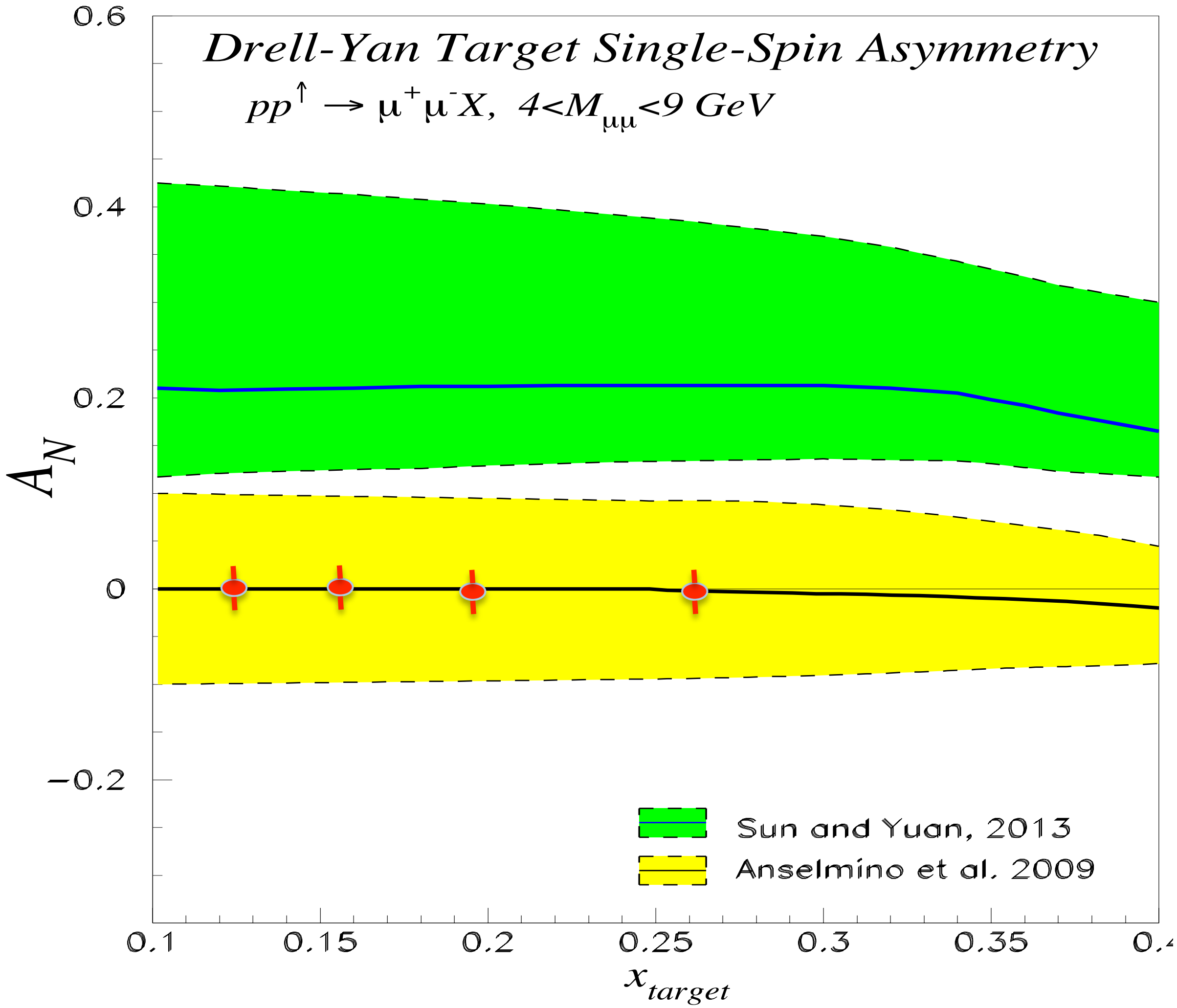
$\Delta\Sigma_q \approx 25\%$

$2\ L_q \approx 46\%$ (0%(valence)+46%(sea))

$2\ J_g \approx 25\%$

K.-F. Liu *et al* arXiv:1203.6388

Projected Statistical Precision with a Polarized Target at SeaQuest



Polarized target

- Installation in Summer 2016
- Supported with Los Alamos LDRD funds

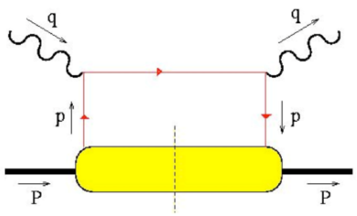
Statistics precision shown for two calendar years of running :

Protons on target = 2.7×10^{18}

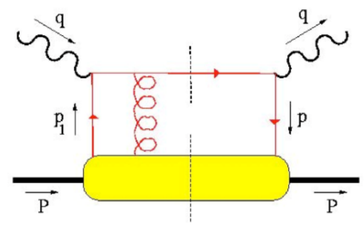
$\mathcal{L} = 7.2 \times 10^{42}$ /cm^2

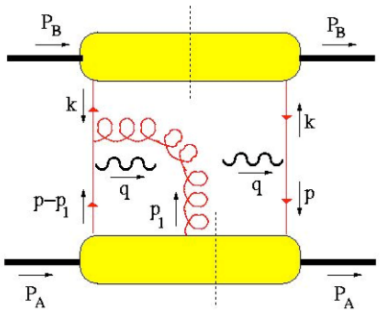
“Naïve” T-odd observables

- Naïve T-odd effect ($F_{1T}^{\perp q}$) must arise from interference between spin-flip and non-flip amplitudes w/different phases

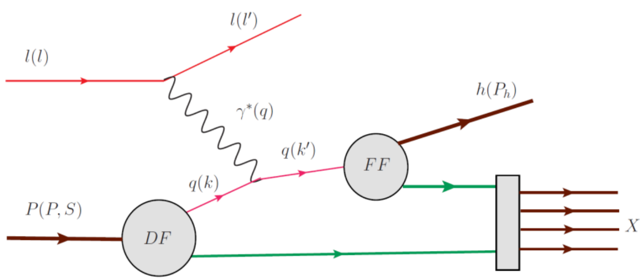


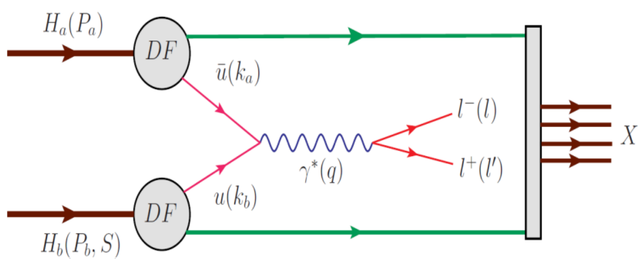
can interfere with





- soft gluons “gauge links” required for color gauge invariance
- soft gluon re-interactions are final (or initial) state interactions … and may be process dependent!





spacelike (DIS) **vs.** **Timelike (Drell-Yan)** **virtual photon**

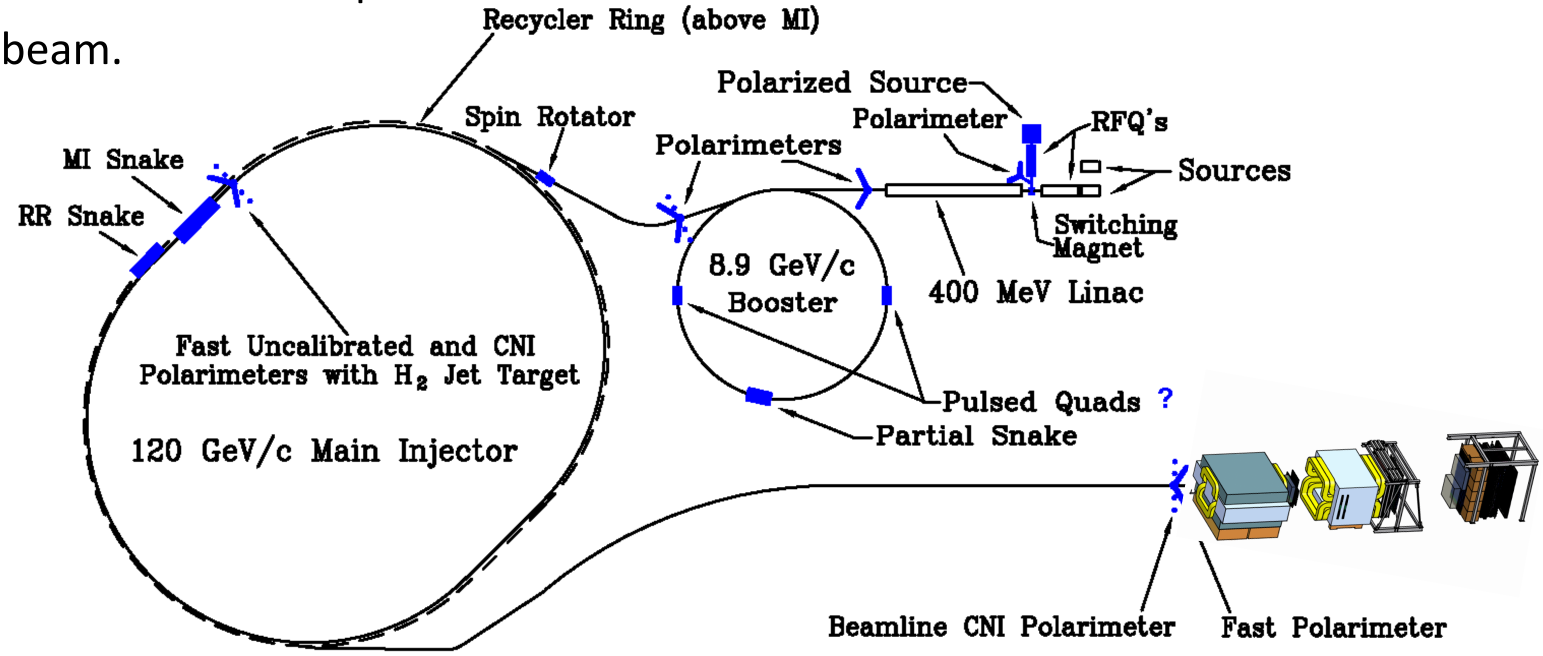
$$f_{1T}^{\perp}\Big|_{\mathrm{SIDIS}} = - f_{1T}^{\perp}\Big|_{\mathrm{DY}}$$

A. Kotzinian, DY workshop, B. CERN, 4/10

Polarized Beam Drell-Yan at Fermilab

The Plan:

- Use fully understood SeaQuest Spectrometer
- Add polarized beam.



Polarized Beam Drell-Yan at Fermilab

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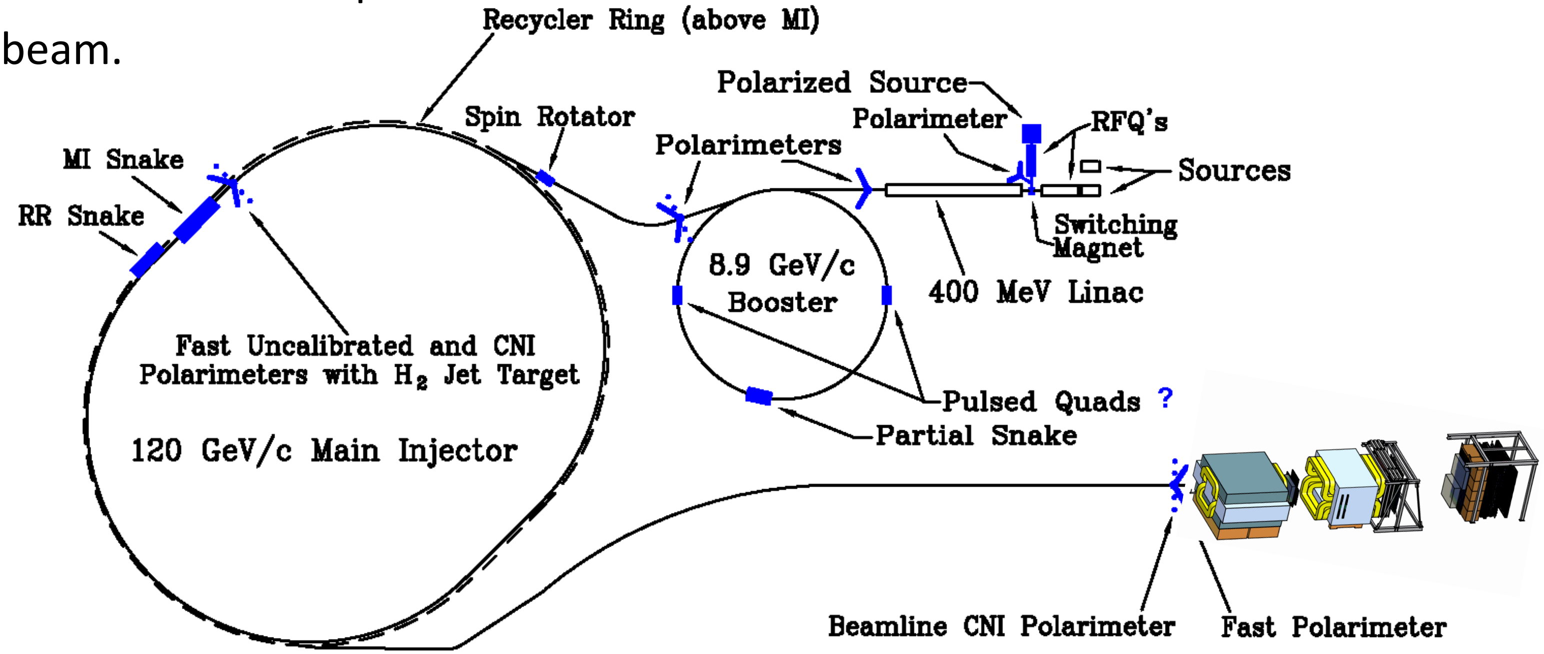
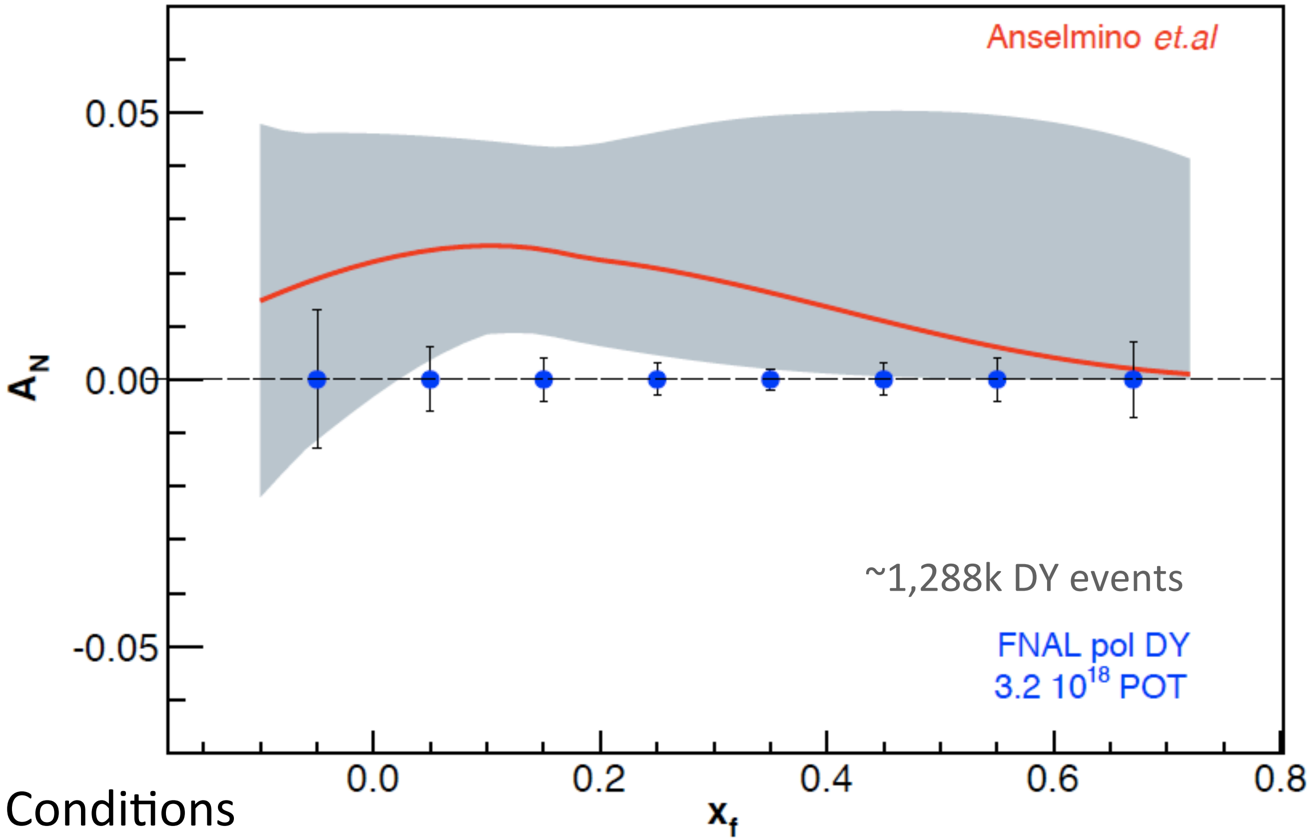


- **Cost Est.: $6M +$4M Contingency & Management = $10M** (in 2013)

Expected Precision from E-1027 at Fermilab

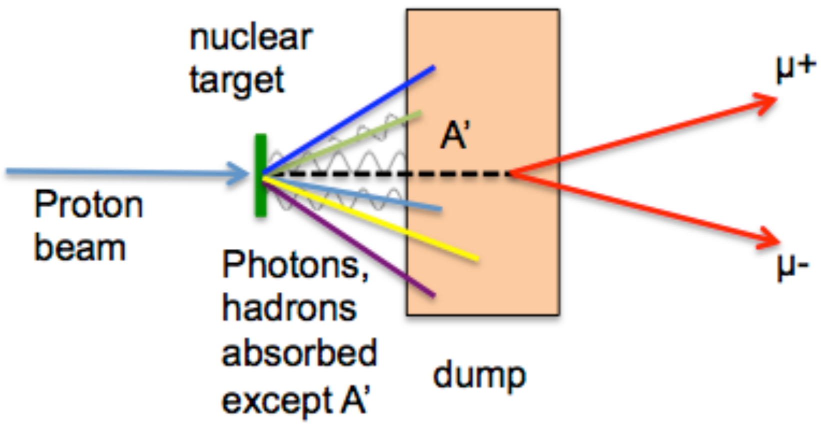


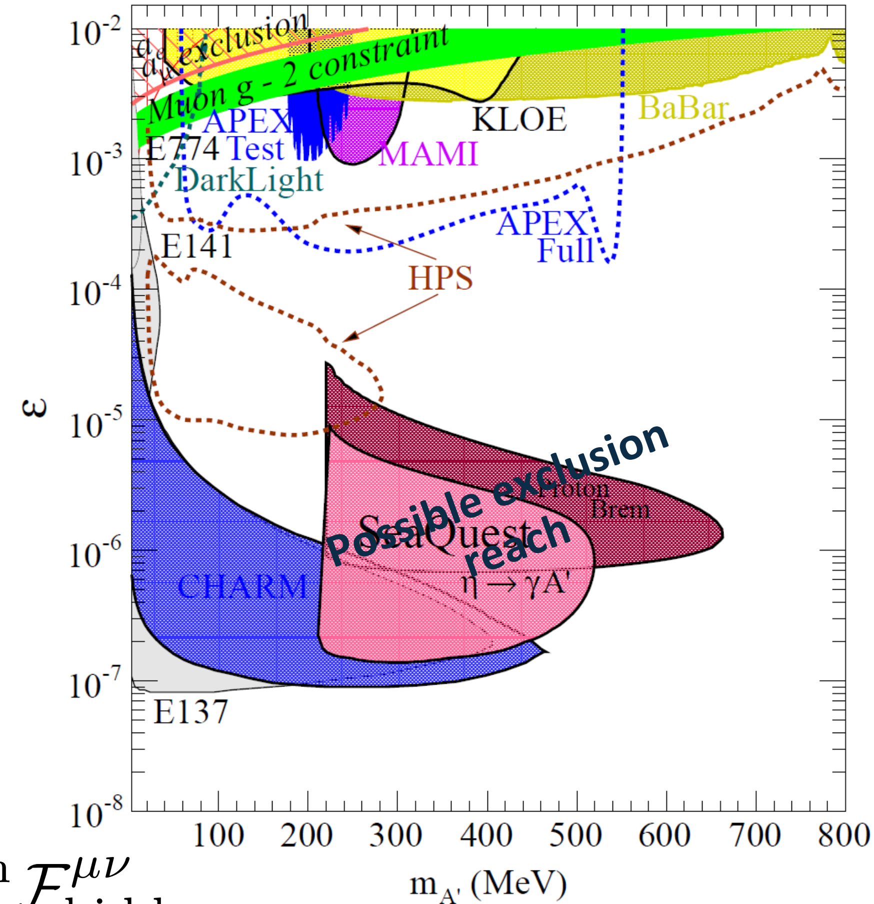
- Experimental Conditions
  - Same as SeaQuest
  - luminosity: L_{av} = 2 x 10^{35} (10% of available beam time: I_{av} = 15 nA)
  - 3.2 X 10^{18} total protons for 5 x 10^5 min: (= 2 yrs at 50% efficiency) with P_b = 70%

Can measure not only sign, but also the size & maybe shape of the Sivers function!

Search for Dark Photons at SeaQuest

- Classic Beam Dump Experiment





- Minimal impact on Drell-Yan program

$$\mathcal{L} \propto -\frac{1}{4}\mathcal{F}^{\mathrm{SM}}_{\mu\nu}\mathcal{F}^{\mu\nu}_{\mathrm{SM}} - \frac{1}{4}\mathcal{F}^{\mathrm{hidden}}_{\mu\nu}\mathcal{F}^{\mu\nu}_{\mathrm{hidden}} + \frac{1}{2}\epsilon\mathcal{F}^{\mathrm{SM}}_{\mu\nu}\mathcal{F}^{\mu\nu}_{\mathrm{hidden}} + m^2_{A'}A^{\mathrm{hidden}}_{\mu}A^{\mu}_{\mathrm{hidden}}$$

Fermilab Polarized Drell-Yan Collaborating Institutes

Polarized Target:

Argonne National Laboratory
Fermi National Accelerator Laboratory
Institute of Physics, Academia Sinica
KEK
Ling-Tung University
Los Alamos National Laboratory
University of Maryland
University of Michigan
University of New Hampshire
National Kaohsiung Normal University
RIKEN
Rutgers University
Thomas Jefferson National Accelerator Facility
Tokyo Tech
University of Virginia

Andi Klein and Xiaodong Jiang
Co-Spokespersons

Polarized Beam:

Abilene Christian University
Argonne National Laboratory
University of Basque Country
University of Colorado
Fermi National Accelerator Laboratory
University of Illinois
KEK
Los Alamos National Laboratory
University of Maryland
University of Michigan
RIKEN
Rutgers
Tokyo Tech
Yamagata University

Wolfgang Lorenzon and Paul E Reimer
Co-Spokespersons

Fermilab E906/SeaQuest Collaboration

Abilene Christian University
Ryan Castillo, Michael Daugherity, Donald Isenhower, Noah Kitts, Lacey Medlock, Noah Shutty, Rusty Towell, Shon Watson, Ziao Jai Xi

Academia Sinica
Wen-Chen Chang, Shiu Shiuan-Hao

Argonne National Laboratory
John Arrington, Don Geesaman*, Kawtar Hafidi, Roy Holt, Harold Jackson, Michelle Mesquita de Medeiros, Bardia Nadim, Paul E. Reimer*

University of Colorado
Ed Kinney, Po-Ju Lin

Fermi National Accelerator Laboratory
Chuck Brown, Dave Christian, Gabriele Garzoglio, Su-Yin (Grass) Wang, Jin-Yuan Wu

University of Illinois
Bryan Dannowitz, Markus Diefenthaler, Bryan Kerns, Hao Li, Naomi C.R Makins, Dhyaanesh Mullagur R. Evan McClellan, Jen-Chieh Peng, Shivangi Prasad, Mae Hwee Teo, Mariusz Witek, Yangqiu Yin

KEK
Shin'ya Sawada

Los Alamos National Laboratory
Gerry Garvey, Xiaodong Jiang, Andreas Klein, David Kleinjan, Mike Leitch, Kun Liu, Ming Liu, Pat McGaughey

Mississippi State University
Lamiaa El Fassi

University of Maryland
Betsy Beise, Andrew (Yen-Chu) Chen

University of Michigan
Christine Aidala, McKenzie Barber, Catherine Culkin, Vera Loggins, Wolfgang Lorenzon, Bryan Ramson, Richard Raymond, Josh Rubin, Matt Wood

National Kaohsiung Normal University
Rurngsheng Guo

RIKEN
Yuji Goto

Rutgers, The State University of New Jersey
Ron Gilman, Ron Ransome, Arun Tadepalli

Tokyo Tech
Shou Miyaska, Kei Nagai, Kenichi Nakano, Shigeki Obata, Toshi-Aki Shibata

Yamagata University
Yuya Kudo, Yoshiyuki Miyachi, Shumpei Nara

*Co-Spokespersons

Subject: RE: Talk at CTEQ-POETIC meeting
From: "Nadolsky, Pavel" <nadolsky@physics.smu.edu>
Date: 11/10/16, 17:53
To: "reimer@anl.gov" <reimer@anl.gov>

Dear Paul,

your talk at CTEQ-POETIC meeting is scheduled on Friday, 11am EST, for 35+5 minutes.
[It's a little shorter than I originally hoped, but the time limits are not strict, if you need a bit of extra time.]

See you at the meeting next week!

Best regards,

Pavel

--

Pavel Nadolsky
Associate Professor
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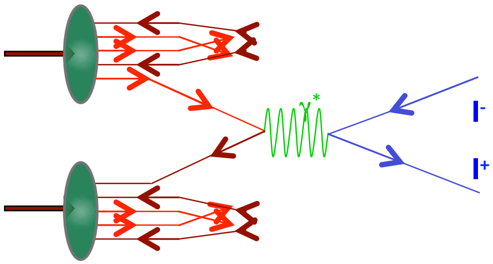
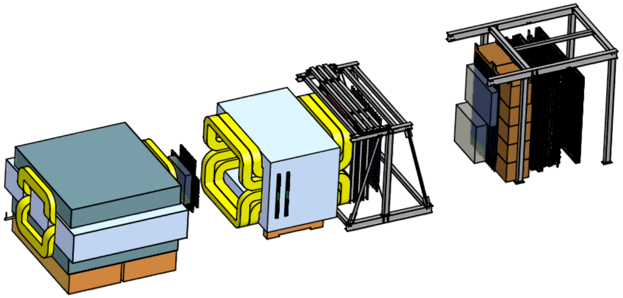
Google Scholar: bit.ly/nadolsky_scholar
Appointments: doodle.com/pavelnadolsky

Drell-Yan Physics Program



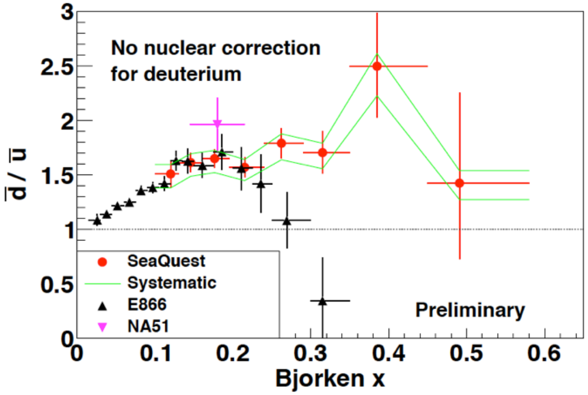


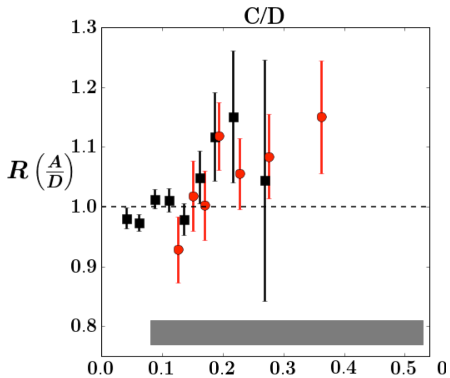
Sea Quarks of the Target

- dbar/ubar
- Sea quark EMC effect

Not discussed:

- Quark sea absolute magnitude
- Partonic Energy Loss
- J/ψ Nuclear Dependence
- Dark Photons?





Transverse Spin Physics

- Sivers and OAM of Sea Quarks
- Sivers and QCD on Valence Quarks (COMPASS and SeaQuest)